Potentials, consequences and trade-offs of terrestrial carbon dioxide removal: Strategies for climate engineering and their limitations

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Abstract

For hundreds of years, humans have engineered the planet to fulfil their need for increasing energy consumption and production. Since the industrial revolution, one consequence are rising global mean temperatures which could change by 2°C to 4.5°C until 2100 if mitigation enforcement of CO_2 emissions fails.To counteract this projected global warming, climate engineering techniques aim at intendedly cooling Earth's climate for example through terrestrial carbon dioxide removal (tCDR) which is commonly perceived as environmentally friendly. Here, tCDR refers to the establishment of large-scale biomass plantations (BPs) in combination with the production of long-lasting carbon products such as bioenergy with carbon capture and storage or biochar.

This thesis examines the potentials and possible consequences of tCDR by analysing land-use scenarios with different spatial and temporal scales of BPs using an advanced biosphere model forced by varying climate projections. These scenario simulations were evaluated with focus on their carbon sequestration potentials, trade-offs with food production and impacts on natural ecosystems and climate itself.

Synthesised, the potential of tCDR to permanently extract CO_2 out of the atmosphere is found to be small, regardless of the emission scenario, the point of onset or the spatial extent. On the contrary, the aforementioned trade-offs and impacts are shown to be unfavourable in most cases. In a high emission scenario with a late onset of BPs (i.e. around 2050), even unlimited area availability for tCDR could not reverse past emissions sufficiently, e.g. BPs covering 25% of all agricultural or natural land could delay 2100's carbon budget by no more than two or three decades (equivalent to ≈550 or 800 GtC tCDR), respectively. However, simultaneous emission reductions and an earlier establishment of BPs (i.e. around 2035) could result in strong carbon extractions reversing past emissions (e.g. six or eight decades or ≈500 or 800 GtC, respectively). In both cases, land transformation for tCDR leads to high "costs" for ecosystems (e.g. biodiversity loss) and food production (e.g. reduction of almost 75%). Restricting the available land for BPs by these trade-off constraints leaves very small tCDR potentials (well below 100 GtC) despite a near-future onset (in 2020). Similarly, simulated tCDR potentials on dedicated BP areas defined in a commonly used and published low emissions scenario stay below the aimed values using current management practices. Some potential may lie the reduction of carbon losses from field to end-products, new management options and the restoration of degraded soils with BPs.

This thesis contradicts the assumption that tCDR could be an effective and environmentally friendly way of complementing or substituting strong and rapid mitigation efforts.

Zusammenfassung (German)

Seit Jahrhunderten formen Menschen die Erde, um sie an ihre Ansprüche nach steigender Produktion und Energieverfügbarkeit anzupassen. Spätestens seit der industriellen Revolution sind eine Folge dessen die steigenden globalen Mitteltemperaturen mit Änderungen von 2°C bis 4.5°C bis 2100 sollten CO_2 Emissionen nicht oder nur unzureichend gesenkt werden. Klima-Engineering befasst sich deshalb mit der gezielten Abkühlung des Klimas, z.B. durch die als generell umweltfreundlich angesehenen Techniken des terrestrische Kohlendioxidentzugs (tCDR). Insbesondere wird der Anbau von großflächigen Biomasseplantagen (BP) in Kombination mit der Erstellung von langlebigen Kohlenstoffprodukten wie Bioenergie oder Biokohle in Betracht gezogen.

Die vorliegende Doktorarbeit untersucht die tCDR Potentiale und möglichen Konsequenzen von BP auf Nahrungsmittelproduktion, Ökosysteme und das Klima selbst mit Hilfe der Analyse von Landnutzungszenarien. Diese Szenarien decken unterschiedliche zeitliche und räumliche Ausdehnungen von BP ab und werden mit einem renommierten Biosphärenmodell unter Einfluss verschiedener Klimaprojektionen simuliert und anschließend ausgewertet.

Insgesamt wird das tCDR Potential von BP als gering befunden, unabhängig vom Emissionsszenario und ab wann oder wie flächendeckend BP angebaut werden. Demgegenüber stehen meist die zuvor genannten, ungewünschten Konsequenzen. Werden in einem Szenario mit hohen CO_2 Konzentrationen BP erst spät (hier 2050) etabliert, kann selbst unbeschränkte Landverfügbarkeit die bisherigen Emissionen nicht ausgleichen: Werden z.B. BP auf 25% aller Landwirtschafts- oder Naturflächen angebaut, könnte dies die atmosphärische Kohlenstofflast in 2100 um nicht mehr als 20 oder 30 Jahre verzögern (äquivalent zu ≈550 bzw. 800 GtC tCDR). Anders jedoch, wenn gleichzeitig Emissionen eingespart und BP früher (hier 2035) angebaut werden (60 oder 80 Jahre Verzögerung äquivalent zu ≈500 oder 800 GtC tCDR). In beiden Fällen führen diese Landumwandlungen jedoch zu sehr hohen "Kosten" für Ökosysteme (z.B. Biodiversitätsverlust) und die Nahrungsmittelproduktion (hier eine Reduzierung um fast 75%). Um deren Schutz zu gewährleisten kann die Landverfügbarkeit für tCDR beschränkt werden, was jedoch die tCDR Potentiale trotz baldiger Etablierung (ab 2020) sehr einschränkt (mit weit weniger als 100 GtC). Auch die Potentiale eines bereits publizierten Mitigationsszenarios bleiben deutlich unter den Anforderungen. Das Potential könnte jedoch durch Erhöhung der Umwandlungseffizienzen von Biomasse, neuen Managementoptionen oder der Aufwertung degradierter Flächen durch BP erhöht werden.

Diese Doktorarbeit kann abschließend nicht die Annahme unterstützen, dass tCDR eine effektive und umweltfreundliche Methode der Kohlenstoffsequestrierung, und damit eine Ersetzung von strengen Mitigationspfaden, sein könnte.

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Abbreviations, units and unit conversions

AF Re- and Afforestation projects

BECCS Bioenergy with Carbon Capture and Storage

BFT Bioenergy Functional Type

BG Bioenergy grasses, herbaceous bioenergy plants

BP Bioenergy plantation

BT Bioenergy trees, woody bioenergy plants

CCS Carbon Capture and Storage

CE Climate engineering

CE-Land Climate Engineering on Land

CFT Crop Functional Type

GMT global mean temperature

PFT Plant Functional Type

RF Radiative Forcing

SRM Solar Radiation Management

tCDR terrestrial Carbon Dioxide Removal

AR5 Fifth Assessment Report

CMIP3 Coupled climate model intercomparison project phase three

CMIP5 Coupled climate model intercomparison project phase five

DFG Deutsche Forschungsgesellschaft (German research foundation)

FAO Food and Agricultural Organization of the United Nations

INDC Intended Nationally Determined Contributions

IPCC International Panel on Climate Change

RCP Representative Concentration Pathway

SPP Schwerpunktprogramm (Priority Program)

UNFCCC United Nations Framework Convention on Climate Change

CanESM2 The second generation Canadian Earth System Model (short Can)

HadGEM2-ES Hadley Centre Global Environment Model version 2 (short Had)

IAM Integrated Assessment Model

IMAGE Integrated Model to Assess the Global Environment

IPSL-CM5A-LR Institut Pierre Simon Laplace Climate Model 5A with low resolution (short IPSL)

LPJmL Lund Potsdam Jena model with managed Land

MIROC-ESM-CHEM Atmospheric chemistry coupled version of MIROC-ESM (short MIR)

MPI-ESM-MR/LR Max-Planck-Institute Earth System Model of medium/low resolution (short MPI)

Units and unit conversions

CO_2 carbon dioxide (1CO_2 refers to 0.27 GtC)

kcal Kilocalorie (1 kcal refers to 1000 calories and equals 4184 J)

kcal cap^{-1} day^{-1} kilo calories per capita and day

ha hectare (1 ha refers to 10,000 m^2)

Mha Million hectares (1 Mha refers to 10^6 ha and 10,000km^2)

Gha Giga hectares (1Gha refers to 1,000 ha refers to 1,000 ha)

CH_4 methane

t ton (metric) (refers to 1,000 kg = 10^6 g)

GtC giga tons of carbon (1 GtC refers to 10^{15} gC and 3.66 $GtCO_2$)

ppm parts per million (1 ppm CO_2 refers to 2.12 GtC)

J Joule

EJ Exajoules = 10^{18} joules (with 18.5 megajoules energy content per kilogram of dry matter)

ZJ Zettajoules = 1000 exajoules

bn billion (1bn refers to 10^9)

1 General introduction to terrestrial Carbon Dioxide Removal (tCDR)

In this thesis, I explore the possibilities and implications of climate engineering (CE) by human kind via employing the terrestrial biosphere as a tool. Simply spoken, CE options have been proposed to decrease global mean temperatures (GMTs) while emissions are reduced at lower rates or continue to rise. The motivation for the proposal of such CE options is given by most climate change projections which show an increase of the GTM between 2 and 4.5°C until 2100 due to insufficient emission reductions. The specific idea of the here investigated CE method is that terrestrial vegetation extracts CO_2 out of the atmosphere, transforms it into biomass carbon using photosynthesis and that this biomass carbon can then be utilised in a smart, permanent carbon-binding way. The expansion of existing vegetation into large-scale biomass plantations should therefore, theoretically, enhance the carbon extraction potential. However, the biophysical potentials and trade-offs for the environment and human well being remain to be studied.

This chapter begins with an overview over the past and current human interferences with the land surface and climate (Section 1.1). Following up on that, I will introduce the terrestrial carbon cycle to explain past and current disturbances and the basic idea of using the terrestrial vegetation as a CE tool (Section 1.2). Why CE methods are proposed at all is presented by looking at recent studies on possible climate change projections and impacts (Section 1.3). Finally, I provide a detailed description of CE methods with a focus on the here investigated terrestrial Carbon Dioxide Removal (tCDR) techniques (Section 1.4). This includes their specific characteristics, the current views on their performance and the unsolved research gaps which this thesis attempts to close. Lastly, I present the structure of the following chapters before briefly explaining the main methods used in this study.

1.1 Living on an engineered planet

Homo sapiens, began to substantially alter the Earth's surface since the beginning of the Holocene 11,700 years ago. This date not only marks the current, stable interglacial period (the warm phase between two glaciations) but also the origin of agriculture, referred to as the Neolithic revolution (e.g. Weisdorf, 2005) 10,000–4000 years ago. Due to the development of language, humans could transmit and evolve their knowledge about tools and techniques. Permanent settlements, the domestication of animals and plants and the constant increase of energy input for food production (e.g. fertilizer, irrigation) allowed the world population to grow: from 50 million people 4000 years ago by a factor of ten until 500 years ago, with a doubling in the 19th century, accelerated up to 7.5 billion people today (Lenton, 2011; United Nations and Affairs, 2015). The growth in food supply was soon built on the exploitation of landscapes: deforestation to create pastures or degradation or salination of soils through malpractices. The invention of the steam engine and the domestic use of coal in the late 18th century led not only to an agricultural revolution but also started the industrialisation. Since that time, food production no longer depends on solar power alone, but is fossil-fuel based through the production of fertilizers and the mechanisation of human or animal power (Evans, 1998). Especially since the 1950s, we humans accelerated not only food production and population growth but yet again the impacts on the environment. Keeling (Keeling, 1960; Keeling et al., 2005) was the first to directly measure the increase in atmospheric carbon dioxide (CO_2) concentration originating mainly from land-use and land cover change emissions and fossil fuel burning. But also the increase of other greenhouse gases such as methane or pollutants causing stratospheric ozone depletion was discovered (Lovelock et al., 1973). Crutzen (2006b) realised that humans have been dominating the planet since the industrialisation and suggested a new geological epoch, the Anthropocene.

Science has progressed and by today we know, that there is a tight relationship between high atmospheric CO_2 and other greenhouse gas concentrations and climate change (e.g. Stocker, 2013). In the history of the Earth there have been times with higher CO_2 concentrations (e.g. during the Paleocene-Eocene thermal maximum (PETM) 55 million years ago lasting for 170,000 years, Röhl et al., 2007). However, it has not changed within such a short time since the last 800,000 years (Stocker et al., 2013b) and never were more than soon 9 billion people affected by it (in 2050, United Nations and Affairs, 2015). Atmospheric CO_2 concentrations have increased from 280 ppm in pre-industrial times to 315 ppm in 1958 (Keeling, 1960) to more than 400 ppm in 2015 (Dlugokencky and Tans, 2016). Despite all climate negotiation efforts since the foundation of the

United Nations Framework Convention on Climate Change (UNFCCC) in 1992, CO_2 concentrations are still on the rise following a “business-as-usual” pathway towards more than 1000 ppm by the end of the 21^{st} century (Riahi et al., 2011). Already today, climate change impacts manifest themselves in increasingly frequent droughts, floods, cold spells or heat waves (Herring et al., 2015; Coumou et al., 2015). Nevertheless, human kind carries on with the exploitation of finite fossil-fuel reservoirs instead of investing in clean renewable energy, continues to produce waste instead of recycling materials and threatens natural ecosystems instead of conserving our last resorts. While the farmers after the Neolithic revolution were not aware of their impacts on the environment and climate, human kind has knowingly and consciously continued to change the planet for the past sixty years.

Any type of engineering follows the principles of applying scientific knowledge in order to solve a problem in the real world through designing and creating tools in a cost effective and practical way (Koen, 1985). The task in the past was mainly to feed a growing world population. The additional challenge the world’s populations faces now is climate change. Our species has proven to be equipped with imagination and creativity which enables us to be innovative (Lenton and Watson, 2011) — so could we possibly engineer a cooler planet if we don’t stop emitting carbon?

1.2 The terrestrial carbon cycle

The title of this thesis hints at the interaction (“removal”) of the land (“terrestrial”) with the atmosphere (“carbon dioxide”). This linkage and the processes tied to it are described in the following to illustrate the origin of the idea of the terrestrial biosphere as a CE method.

1.2.1 Natural land carbon sinks and sources

The global carbon cycle describes a closed chain of processes relevant for exchanging carbon between storage compartments in the atmosphere, ocean and land (see Fig. 1.1). Mainly CO_2, but also methane (CH_4) or black carbon, are part of the atmospheric carbon reservoir and exchanged with the land and oceans on short to long timescales following biogeochemical or dynamical processes.

The natural land surface consists of rocks and bare, vegetated or watered soils. It takes millennia for rocks and bare soils to extract carbon out of atmosphere by the process

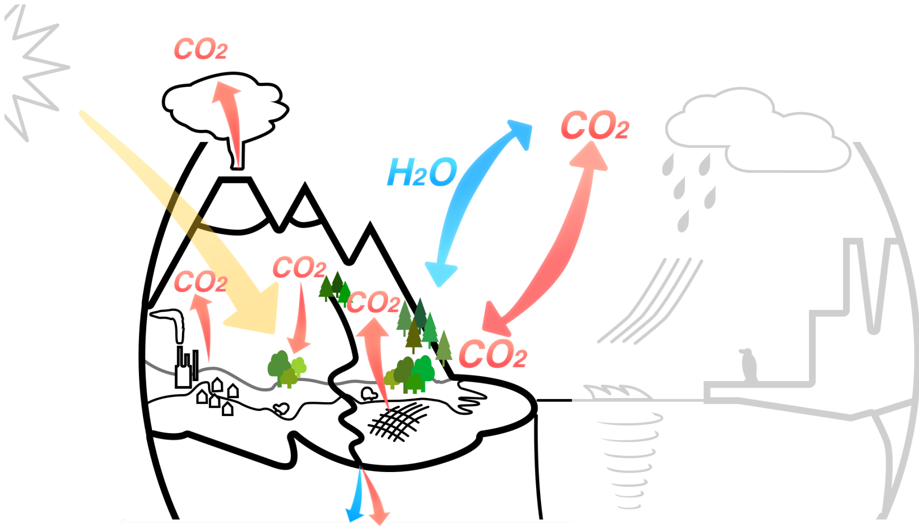

Figure 1.1: Illustration of the terrestrial carbon cycle: red arrows refer to carbon fluxes and blue arrows to water fluxes. The focus of the study lies on the carbon exchange between the vegetation and emissions by agriculture or industry.[1]

of weathering while it can be lost on similar time scales through leaching or within days through volcanic eruptions. Phytoplankton in wetlands takes up carbon through photosynthesis on short time scales which can then, over millions of years and under anaerobic conditions, transform to peat lands (sometimes frozen as permafrost soils) or fossil fuels.

Vegetation, however, is dynamic. Plants compete for light, water, space and nutrients forcing them to act on short timescales from minutes to hours to adjust to their optimum growing conditions. Through their leaves plants take up CO_2 from the ambient air and, using light energy, transform it to sugar molecules consisting of carbon which is then stored in cells for growth and the allocation of biomass. Plants can control their physiological processes and even leaf properties to maximise their carbon uptake while minimising water and energy losses. This allows them to store and enrich carbon on annual to decadal time scales or as long as growing conditions are suitable. But plants can also lose carbon on a daily basis: leaves respire approximately half of the plants' annual carbon accumulation during night time. Growing conditions may also become unsuitable through wind, pest or fire disturbances or the replacements or transitions of ecolines through changing climate which induce a transfer of all biomass to litter pools at once. Here, microbes decompose this biomass of which most parts are released back

[1]The background figure (all black lines) reached the top five in the AGU 2015's T-Shirt contest of the Earth and Planetary Surface Processes' group.

to the atmosphere while the remaining carbon is transformed to soil organic matter. As described here, the carbon cycle is closed and undisturbed and the biosphere represents a carbon sink (net carbon uptake).

1.2.2 Anthropogenic land carbon sinks and sources

Since the Neolithic revolution (see 1.1) humans have changed the natural characteristics of the carbon cycle by land-use and land cover change. Forests were and are still cleared for the use as fuel, building material or to free land for agriculture whereby agriculture itself causes soil erosion and desertification in some areas. Ever since the transformation of land started, large amounts of carbon have been released to the atmosphere (approximately 145±50 giga tons of carbon (GtC) between 1870 and 2014, House et al., 2002; Quéré et al., 2015) which might otherwise have been stored in the land for decades or centuries. But also the anthropogenic drainage of peat land, burning of turf and, especially, fossil fuels (400±20 GtC) and the melting of permafrost soils release long-stored carbon. Land-use and land cover changes as well as the burning of fossil fuels represent a carbon source.

Especially the burning of fossil reservoirs disturbs the carbon cycle since more carbon is released in a relatively short time than could ever be extracted by natural processes on decadal or centennial time scales. At present, approximately 10–20% of the atmospheric CO_2 will remain airborne for millennia (Archer and Brovkin, 2008) until removed by weathering. However, during the last 50 years, the terrestrial vegetation has increased its productivity, partly due to a changing climate but mainly due to the increasing CO_2 concentration acting as a fertilizer. Therefore, the land carbon sink has increased from 1.7±0.7 GtC yr^{-1} in the 1960s to 3.0±0.5 GtC yr^{-1} between 2005 and 2014 and thus, balances more than the net land-use flux into the atmosphere of currently 1.0±0.5 GtC yr^{-1} (Quéré et al., 2015).

The idea of using the biosphere to decrease the global CO_2 concentration origins from the following observations: the expansion of global vegetation in combination with enhanced productivity under climate change could “artificially” increase the land carbon sink. To further boost the projected outcome, fast growing plant species could be chosen in a highly managed environment. Ideally, these plants do not decay at the end of their lifetime but are collected and transformed in long-lived carbon products or storages to prevent a carbon release. Thereby, this biomass is not only climate neutral but could also lead to negative emissions if its carbon is permanently excluded from carbon cycle processes. This strategy is called terrestrial Carbon Dioxide Removal (tCDR) which is described in more detail in the following Section 1.4. However, the strength and limits of the CO_2 fertilization effect and the impacts of heat and water stress on plant productivity are still being researched (e.g. Cramer et al., 2001; Leipprand and Gerten, 2006; Müller et al., 2007; Luo et al., 2008; Friend et al., 2014).

1.3 Challenges posed by climate change

The need for emission reductions, either through mitigation or tCDR, arises from the already occurring and the expected impacts of climate change on the environment and societies. Although the climate has always been changing on this planet, the setting is different this time: the current climate warming is not only caused by rapid anthropogenic emissions, it in turn also affects a growing world population of soon 9 bn people (United Nations and Affairs, 2015) living on this planet. More than twenty years back, the UNFCCC agreed on limiting greenhouse gas concentrations at levels that "prevent dangerous anthropogenic (human induced) interference with the climate system" (Rogner et al., 2007). Since then, scientific and non-scientific approaches are used to analyse, identify and define at what level of climate change the risk of the climate system, ecosystems, food production and economic development to experience dangerous impacts is likely. Recent studies confirmed, that impacts on these components might be severe for as little as 2°C of warming above pre-industrial times (Gerten et al., 2013; Ostberg et al., 2013; Warszawski et al., 2014; Arnell et al., 2014; Schellnhuber et al., 2016). Already today, the occurrence of extreme weather events can be attributed to climate change in some regions (e.g. Diffenbaugh et al., 2015; Herring et al., 2015; Lehmann et al., 2015). During the last climate negotiations even a target of 1.5°C was requested (Rogelj et al., 2015c) to protect also the most vulnerable regions since countries can bear different levels of such change. It is due to these ambitious mitigation targets, that proposals like tCDR have entered the stage of global climate projections.

Especially since the fifth assessment report (AR5) of the International Panel on Climate Change (IPCC) studies have been put forward to analyse the impacts of each unit of warming on ecosystems. Using different metrics, models and focuses, these studies commonly find habitat transformations or shifts in biogeochemical functioning and structures of ecosystems beginning at 2°C (Gerten et al., 2013; Ostberg et al., 2013; Warszawski et al., 2014). These changes first put ecosystems mainly at high latitudes at risk affecting up to one fifth of the land surface and, with progressing warming of up to 3.5°C, also tropical regions are affected with areas twice as large. Already today, species loss increases exponentially due to human interferences including land-use change(Ceballos et al., 2015). The transformation of ecosystems also affects human well being. Not only have natural spaces an emotional value (Chan et al., 2016), but they also regulate our climate, provide us with clean air and thus, contribute to our health.

Climate change directly affects us through altering global circulation patterns, increasing frequency and strength of extreme weather events (Lehmann et al., 2015) and sea-level rise (Levermann et al., 2013). Global water scarcity and harvest failures could severely increase above a warming of 2°C (Gerten et al., 2013; Piontek et al., 2014) affecting millions of people. Especially droughts and changing monsoon patterns, or e.g. the absence of vital rainfall events in Africa (Gan et al., 2016), will increasingly cause severe humanitarian situations and force thousands of people to migrate to different regions — with the potential of political and cultural conflicts (Barnett, 2003; Barnett and Adger, 2007; Black et al., 2013).

Humans have changed and exploited the planet for hundreds of years with the consequence of rapidly proceeding climate change. We humans know that we have to prevent the "risk of dangerous climate change" — either by enforcing rapid mitigation or by considering climate engineering options like tCDR. The question arises if tCDR actually has the potential to reduce climate change and if so, wether its impacts are not repeating and enhancing past human interferences with the Earth system.

1.4 terrestrial Carbon Dioxide Removal (tCDR) in the context of climate engineering (CE)

Having introduced past human impacts on land cover and the atmosphere and the idea of using biomass plantations to avert projected climate change, I will now focus on the concept of tCDR in more detail.

1.4.1 Current and future climate change: the failures, needs and hopes

Atmospheric CO_2 concentrations have increased by more than 120 parts per million (ppm) since pre-industrial times with $\sim$280 ppm (Keeling and Whorf, 2005) which corresponds to a carbon load of about 545$\pm$55 GtC (400$\pm$20 GtC from fossil fuel burning plus 145$\pm$50 GtC from land-use and landcover change, Quéré et al. (2015)) and a GMT increase of 1°C in 2015 relative to the 1880–1920 period (Hansen et al., 2010). The agreement filed by the parties during the negotiations in Paris 2015 aims at limiting the GMT increase to 2°C or even 1.5°C by 2100. Analogously, this likely limits the allowed additional emissions to 260 GtC or 110 GtC, respectively, for the period of 2011–2100 (Rogelj et al., 2015b). However, the intended nationally determined commitments (INDCs) could so far only achieve an emission reduction still leading to 2.7°C of warming (Jeffery et al., 2015) — without any legally binding enforcement. In fact, current carbon emissions even exceed the highest projections for today made by the Representative Concentration Pathway (RCP, van Vuuren et al., 2011a) with a radiative forcing of 8.5 W m^{-2} (RCP8.5, Riahi et al., 2011) in 2100 (Peters et al., 2013; Smith et al., 2016).

The global energy system needs to transform rapidly within the next two decades to attain the success of climate mitigation (Kriegler et al., 2013; Stocker et al., 2013a; Rogelj et al., 2015a; Rogelj et al., 2015d). This transformation process has to be pushed forward against the long-established political and socio-economic structures promoting the use of fossil fuel energies (Bertram et al., 2015; Edenhofer, 2015). However, despite the efforts to achieve a climate stabilisation by 2100, failure of such transformation is still possible.

1.4.2 CE methods to conquer mitigation failures

To prepare for possible mitigation failures, climate engineering (CE) options have been proposed to artificially reduce the radiative forcing (RF) of the Earth to lower GMTs. The purpose of CE could be to decrease GMTs permanently in case of a dangerous climate change (Crutzen, 2006a) or to delay warming and to allow for technological and structural lock-ins to be overcome (Keith, 2013). This could theoretically be achieved following two different strategies (Fig. 1.2). The first addresses all techniques that monitor the amount of radiation captured in the atmosphere by, for example, increasing the amount of incoming sunlight reflected back to space. These techniques are grouped under the term Solar Radiation Management (SRM). While SRM addresses the symptoms but not the cause of climate change, the second strategy of CE aims at permanently extracting carbon out of the atmosphere after it was emitted which is therefore called Carbon Dioxide Removal (CDR). This could be done by direct air capture, enhanced weathering, ocean fertilization or by intentionally increasing the land carbon sink using the global vegetation as described in Section 1.2. Increasing the land carbon sink forms the basis of the studies compiled in this thesis.

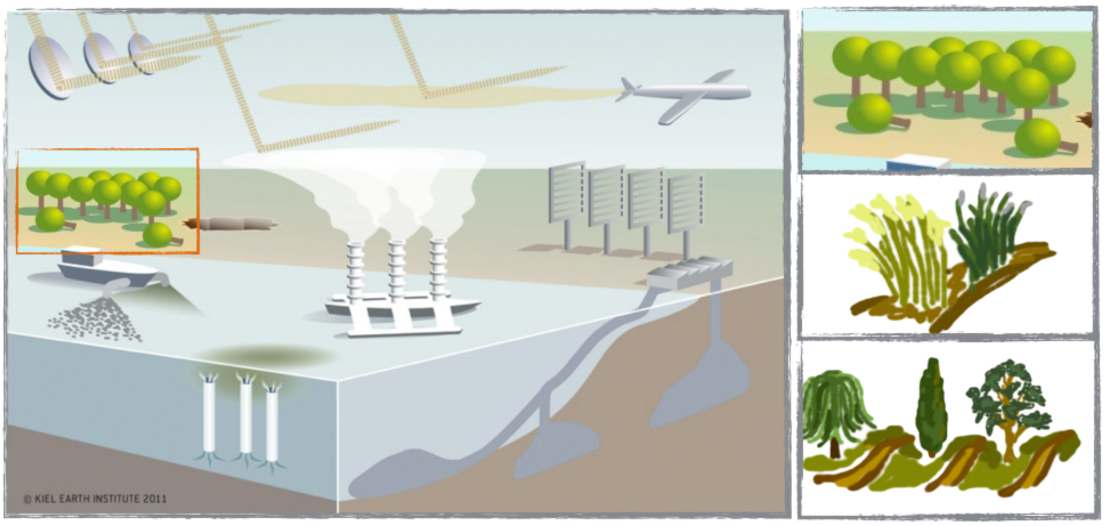

Figure 1.2: Illustration of different CE proposals (light colours) and, specifically, tCDR (orange box) through afforestation or herbaceous and woody bioenergy plants (right panel). Source: `http://www.spp-climate-engineering.de`.

1.4.3 tCDR as a popular climate engineering tool

Terrestrial CDR (tCDR) uses the potential of the global land vegetation to extract as much carbon out of the atmosphere as possible (see previous Section 1.2) for example through the establishment of large-scale biomass plantations (BPs) or re- and afforestation (AF) projects (e.g. Lenton, 2010; Caldeira et al., 2013; Shepherd, 2009). In contrast to AF projects, management of BPs in the form of regular harvest events is needed to keep the productivity of immature plants high. While the permanent forests of AF projects store carbon in the built-up biomass, BPs further need to be accompanied by a suitable carbon utilization pathway to immobilise as much carbon as possible. The harvested biomass must either be converted to long-lived carbon products (e.g. construction material) or permanently stored away (e.g. carbon burial). The most common pathway is the conversion of biomass to biofuels or biochar with subsequent storage of carbon in geological reservoirs, also referred to as bioenergy with carbon capture and storage (BECCS).

Re- and afforestation projects (for commercial use or environmental reasons) have been covering about 278 Mha worldwide between 1990 and 2015 (Keenan et al., 2015). tCDR through vegetation is mostly seen as an environmentally friendly (Midilli et al., 2006) and relatively safe method in the CE portfolio (Shepherd, 2009). In fact, most ambitious mitigation scenarios of the IPCC (Stocker et al., 2013b) already base their confidence on the implementation of BPs or AF to stay around the 2°C target (Fuss et al., 2014; Humpenöder et al., 2014; Popp et al., 2014b; Lomax et al., 2015). For example, RCP2.6

(van Vuuren et al., 2011b) strongly relies on the success of large-scale BPs. BPs could not only substitute fossil fuels, and thus, lead to zero-emissions but could also provide net negative emissions over longer time scales if combined with carbon capture and storage (CCS) (Pongratz, 2013). However, efficient tCDR in the order of projected future emissions in partially to non- mitigated scenarios (RCP4.5 to RCP8.5, van Vuuren et al., 2011a) is also assumed to require much larger areas than in today's AF projects and over long time scales (Caldeira et al., 2013). Despite the popularity of tCDR, its potentials and interferences with the Earth system and human well-being remain to be studied in detail (Fuss et al., 2014). This study presents advances to fill this gap in knowledge.

1.5 The objectives of this study

As pointed out in the previous sections, there are still major open questions concerning the potentials and trade-offs of BPs. The following section will elaborate on these points to finally formulate the goal of this thesis. The main objective, as stated in the title, can be summarised as to comprehensively analyse the carbon extraction potentials of large-scale tCDR plantations and to examine the associated impacts on and trade-offs with ecosystems and human well-being. For this purpose, I use a spatially explicit, process-based model of global vegetation and biogeochemical cycles which will be described briefly in Section 1.7, in detail in Chapters 2–4 and in the supplementary information (SI) D.4.

1.5.1 Current view on tCDR

Previous studies already estimated the potentials of tCDR using literature reviews, field studies and Integrated Assessment Models (IAMs) (see also SI B Table B.2). Of those, only few studies consider tCDR as a CE method with large-scale applications (Lenton and Vaughan, 2009; Lenton, 2010; Vaughan and Lenton, 2011; Caldeira et al., 2013; Keller et al., 2014). Furthermore, in contrast to the idea of CE being a "late-regret" option, most consider an early onset of tCDR actions as of today or 2020 and even simultaneous reduction of emissions like in other large-scale mitigation studies with tCDR (van Vuuren et al., 2007; Reilly et al., 2012; Edmonds et al., 2013; Humpenöder et al., 2014). Most studies therefore find that tCDR can indeed successfully complement mitigation pledges.

1.5.2 tCDR: mitigation pledge or CE method?

Most of the aforementioned studies also reveal discrepancies in the definition of tCDR: either it is applied as a mitigation or as a CE method. Vaughan and Lenton, 2011 argue that avoided deforestation means mitigating climate change whereas AF and BPs alter the land surface which makes them, independent of time and spatial scales, a CE method. This argumentation would be in line with the previous observation that past land-use and land cover changes could already be counted as negative CE actions (e.g. contributing to climate change, see Section 1.1). I here argue that CE methods, especially SRM, are generally discussed in view of dangerous climate change i.e. if climate change impacts become too severe. This justifies a large-scale implementation starting only decades ahead. Commonly, while mitigation methods try to limit future emissions, CE methods also try to compensate for past actions through an "intended" effort to reduce the Earth's RF and thus, climate change (e.g. by achieving negative emissions).

1.5.3 Research gaps

CE actions are thought to be applied intendedly, that is based on a sound knowledge about possible positive and negative consequences. This study scrutinises major prevailing assumptions and fills research gaps in order to build such a knowledge basis on tCDR — before any realisation plans should be considered.

There are already studies that raise concerns about the feasibility of CE methods like tCDR to prevent or conquer climate emergencies (Jamieson, 2013; Barrett et al., 2014; Sanford et al., 2014). For one, the fear persists that research of CE potentials alone could distract from the need for mitigation actions (moral hazard, Corner and Pidgeon, 2014). Possible side-effects of CE techniques are still not completely understood leaving questions about impacts and reversibility open (Sillmann et al., 2015). And last: who decides whether a "climate emergency" is reached (Sanford et al., 2014)?

Doubts recently also increased about the feasibility of BPs to fulfil the expectations raised by earlier studies. Next to questions regarding financial, political and economic feasibility (not explicitly analysed here), the following research questions are still unanswered. These questions point at uncertainties that, in the course of this thesis, will be elaborated upon and, by the end of this thesis be reduced or eliminated.

- Is the tCDR potential of BPs sufficient to lower, balance or even overcompensate different levels of future emissions?

- What would the trade-offs for food production and the impacts on climate and ecosystems be?
- Could natural vegetation capture similar magnitudes of carbon?
- Is there enough land available for the establishment of effective BPs?
- Could technological development save space and time through an increase of efficiency?

The here conducted analysis addresses these uncertainties described in previous publications (e.g. Bronstein, 2010; Dornburg et al., 2010; Beringer et al., 2011; Smith et al., 2013a; Kraxner et al., 2013; Fuss et al., 2014; Slade et al., 2014; Smith et al., 2016). Following the structure described below (Chapter 1.6), this thesis will systematically assess the potentials and obstacles of tCDR. Since the time of interest lies in the future and the objectives are large-scale land transformations, computer simulations are conducted to quantify benefits and disadvantages of tCDR. The computer model applied here, the Lund Potsdam Jena model with managed Land (LPJmL, see SI D.4), is especially appropriate for this task, as previous studies not only compared its representation of natural vegetation and managed land against observations (Cramer et al., 2001; Sitch et al., 2003; Bondeau et al., 2007; Beringer et al., 2011) but also confirmed a reasonable representation of global bioenergy plantations (Heck et al., 2016).

1.5.4 A joint effort to investigate CE proposals

The priority program of the German research foundation (Schwerpunktprogramm (SPP) 1689 der Deutschen Forschungsgesellschaft, DFG) concentrates on the research and public discourse of the "Risks, Challenges and Opportunities?" of climate engineering (`http://www.spp-climate-engineering.de`). This comprehensive framework sheds light on all the CE proposals shown in Fig. 1.2 as well as on political, legal and ethical aspects of the CE discussion. In fact, this SPP is motivated by the claim that research on CE methods is needed to allow for a sound and informed public discourse and to foster alternative, near-future mitigation actions if CE potentials proof to be insufficient, too uncertain or overwhelmed by negative side-effects (Pidgeon, 2013; Fuss et al., 2014; Sanford et al., 2014; Smith et al., 2016).

This thesis contributed to the subproject CE-Land (CE on land, Deutsche Forschungsgesellschaft, 2013) with thorough analyses on the feasibility of tCDR from an Earth system analytical point of view.

1.6 The structure of this thesis

This thesis quantifies the potentials and impacts of tCDR under different assumptions about land availability, emission pathways and onset of tCDR. The overall structure of the main analysis is displayed in Fig. 1.3.

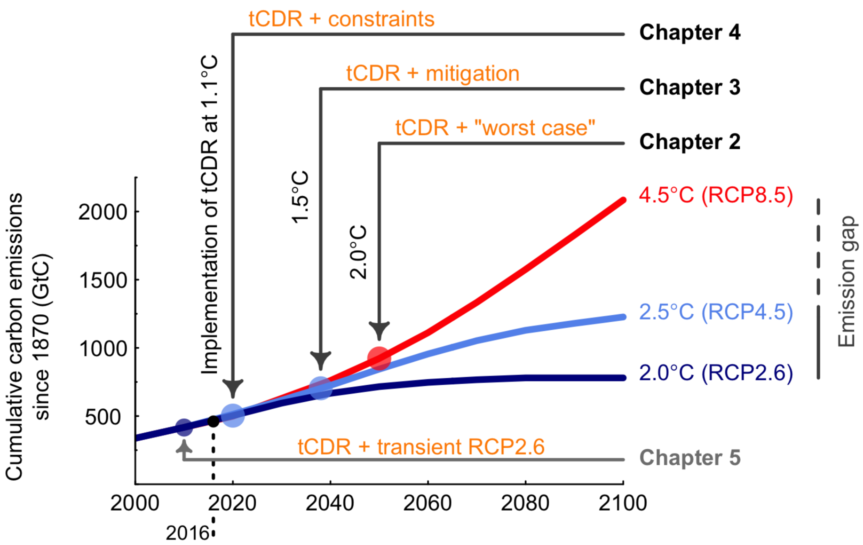

Figure 1.3: Presentation of the structure of this thesis based on different emission scenarios until 2100. Chapter 3 to Chapter 4 assume different starting points of tCDR implementation based on the story lines introduced in this section.

In a first step, tCDR is prioritised compared to trade-off variables such as food supply and ecosystem protection in a business-as-usual (BAU) scenario with tCDR as a "late-regret" option. This means, that tCDR is implemented at the large-scale once the 2°C target is crossed around mid-century to assess the upper ceilings of tCDR potentials in a "worst case" climate scenario. In particular, I investigate by how many years tCDR could delay cumulative emissions of 2100 and at what non-economic "costs" (Chapter 2).

The next step looks at the potentials and trade-offs, if tCDR is implemented in a partially mitigated climate scenario, for example to bridge the emission gap of the current INDCs to limit global warming to 1.5–2°C by 2100. An earlier onset (when the 1.5°C goal is reached in the late 2030s) allows for less drastic applications of tCDR compared to Chapter 2.

In the future, challenges for food production, biodiversity and climate protection will increase and hence, strictly constrain the availability of land for BPs (Chapter 4). Different assumptions about food demand (tied to population growth and dietary trends), yield increases and maps of protected areas as well as unfavourable albedo changes therefore limit the space for BPs and hence, tCDR potentials. The option of assumed technological development could, however, increase these potentials again.

The final analysis focuses on the bioenergy potentials and trade-offs of the mitigation scenario RCP2.6 (Chapter 5) — the only mitigation scenario of IPCC AR5 staying below the 2°C warming target. I reconstruct the land-use patterns of this commonly used scenario to investigate under what conditions and trade-offs the documented and published potentials (van Vuuren et al., 2011b) could be reached. This will give a broader view on the rather extreme cases investigated in the chapters before.

A summary and outlook finalise the study and put the results into perspective. This thesis does not intend to give advice about tCDR but rather could enlighten the public, political and scientific discourse on tCDR.

A separated chapter presents supplementary information (SI) produced in the course of this study. For example, analyses and data sets created within this study are presented that, in the end, did not directly contribute to the finalisation of this work but added to the work of colleagues. Also, being a part of a publicly funded German project, I contributed to the educational "Bildungswiki Klimawandel" of the German Bildungsserver (in German) for pupils and teachers which is also presented here.

1.7 The main methods used in this study

Here, I shortly describe the spatially explicit biogeochemical vegetation model LPJmL (see Fig. 1.4), which forms the basis of this study. So far, there are no large-scale field experiments on tCDR and, moreover, I focus on possible land transitions in the future. Computer simulations and the analysis of large amounts of generated data are therefore inevitable. A thorough description of the model is included in all Chapters 2–4 and in the SI D.4.

Fig. 1.4 shows one exemplary grid cell with an extent of 0.5° x 0.5° including all major model features. Monthly fields of precipitation, temperature and cloudiness as well as annual data of CO_2 concentration drive the dynamically simulated distribution of nine plant functional types (PFT) for the period of 1901–2005 (Ostberg et al., 2015). Each PFT summarises the main attributes and processes related to a certain group of plants such as tropical evergreen trees or boreal needle leave trees. These PFTs compete for light, water and space. Water supply is offered by rainfall, reservoirs and a

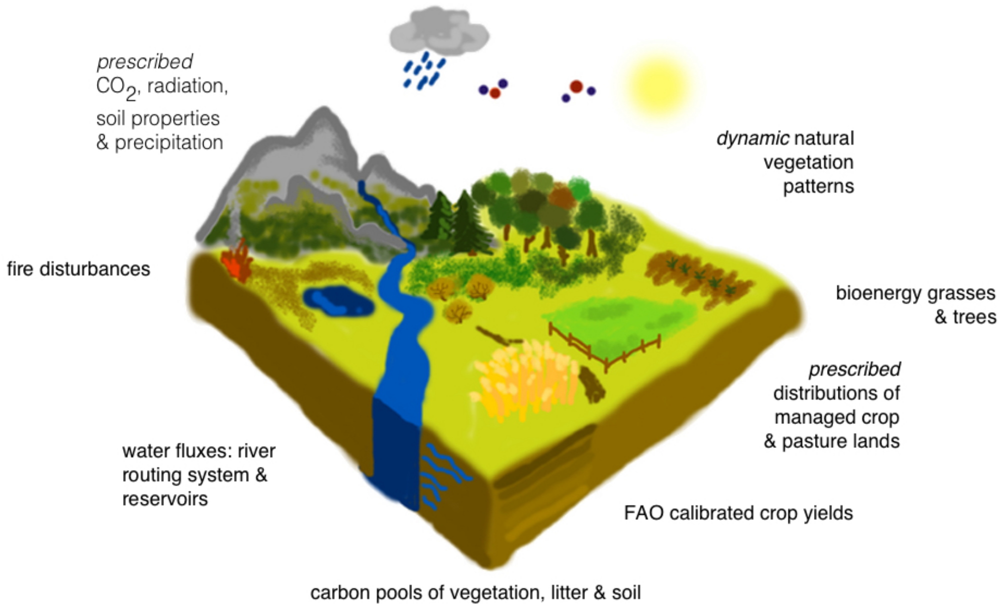

Figure 1.4: Illustration of the main components of the dynamic global vegetation model LPJmL.

river routing system. The distribution and composition of twelve crop functional types (CFT) is prescribed in each grid cell and their yields calibrated with national FAO (Food and Agricultural Organization of the United Nations) data of 1995–2005 (Fader et al., 2010). Crop land can additionally be irrigated as described by Jägermeyr et al. (2015). Two categories cover the representation of "other" food, nutrition and fibre plants (e.g. potatoes, citrus and cotton) and pastures. The distribution of herbaceous bioenergy plants (bioenergy grasses, BG) and woody bioenergy plants (bioenergy trees, BT) is prescribed as well, following specific scenarios designed in each separate study of this thesis. Simulations for the period 2005–2100 are driven by bias-corrected climate scenarios conducted for the coupled climate model intercomparison project phase three (CMIP3) (Heinke et al., 2013).

In a complex post-processing procedure with the open source software R (`https://cran.r-project.org/`) tCDR potentials including conversion pathways are calculated and impacts of BPs analysed. I emphasise that the model does not simulate feedbacks of carbon and biogeophysical alterations between the land and the atmosphere. Therefore, tCDR potentials cannot change the atmospheric CO_2 concentration and thus, GMT reduction potentials can only be approximated (Chapter 2). tCDR potentials rather represent the sole carbon extraction potential in years of emissions saved by 2100 (equal to a slow-down on the trajectory by the given years) or as the additional emissions that could be balanced as presented in Chapter 2 and 3.


Juni '16

2 Limited potential of terrestrial climate engineering to delay Earth's anthropogenic warming[1]

[1]This chapter was submitted with modifications as: L. Boysen, W. Lucht, and D. Gerten and V. Heck (2016). "Limited potential of terrestrial climate engineering to delay Earth's anthropogenic warming". *Earth's Future*.

Abstract

Even though parties agreed in the Paris climate accord to limit global warming to at most 2°C above preindustrial level, it still cannot be precluded that greenhouse gas emissions might evolve along a worst-case, business-as-usual trajectory. Terrestrial Carbon Dioxide Removal (tCDR) through biomass plantations or afforestation has recently been debated as a 'green' climate engineering option to lower global mean temperature (GMT) in case of such failed mitigation, yet the potentials and the wider Earth-systemic side-effects of such measures remain poorly quantified. Based on spatially explicit simulations with an advanced biosphere model, we here systematically quantify the potentials of tCDR to balance continuing CO_2 emissions (after a GMT rise by 2°C will have been reached by mid-century) for a range of scenarios representing different assumptions about which areas are considered for conversion to tCDR plantations. We find that the ability of the biosphere to balance cumulative emissions on a business-as-usual emissions pathway (akin to the Representative Concentration Pathway [RCP] 8.5) is limited to 28–67 years even if major arable areas (4.3–7.4 Gha) were converted. Spatially less extensive conversions (1.1–1.5 Gha) could 'delay' unabated emissions by 13–16 years and, respectively, by 40–45 years on an alternative emissions pathway with partial mitigation (akin to RCP4.5). Besides this limited potential to counteract fossil fuel emissions, any such tCDR scenario would more or less severely compromise ecosystem functioning (e.g. loss of habitats) or food production (likely exceeding future yield increase projections). We conclude that large-scale tCDR is not a viable alternative to ambitious mitigation actions.

2.1 Motivation and objective

In the Paris climate accords of December 2015, the international community of states has agreed on limiting the rise in global mean temperature (GMT) to well below 2°C above preindustrial level (UNFCCC, 2015). Nevertheless, a wide range of actual anthropogenic CO_2 emissions into the atmosphere is still possible. Current pledges agreed upon in the intended nationally determined contributions are voluntary contributions to mitigation (Jeffery et al., 2015) that would not achieve the stated objective. Should they not materialise, not be substantially increased over time, be disrupted, delayed or overpowered by concurrent fossil fuel-based development (Bertram et al., 2015; Smith et al., 2016), a GMT rise of up to 5°C by the end of the century cannot be precluded. It is therefore important to not only analyse pathways of successful decarbonisation (Luderer et al., 2011; Klein et al., 2013; Kriegler et al., 2013; Lomax et al., 2015; Rogelj et al., 2015c) but also less favourable outcomes — risk assessment involves considering the worst cases. In fact, understanding their detrimental implications could be a crucial factor in ensuring success.

To counteract inertia in economic and political developments, climate engineering methods such as terrestrial Carbon Dioxide Removal (tCDR) have been proposed to reduce the risk of reaching a level of "dangerous" global warming (Caldeira et al., 2013; Shepherd, 2009; Vaughan and Lenton, 2011). tCDR via biomass-producing plantations and afforestation is the only presently feasible technology – sometimes referred to as a "green" option (Midilli et al., 2006) – for extracting carbon from the atmosphere after it was emitted. Hence, tCDR can be investigated as a countermeasure to potentially slow down, by partial balancing, the progression of atmospheric CO_2 accumulation in case failed or delayed mitigation leads to increasingly substantial and widespread impacts. However, the ability of the biosphere to fulfil such expectations and the magnitude of incurred side effects remains largely unstudied in detail. Although several estimates of the potential of tCDR as climate engineering method to modify emission pathways have been published (Caldeira et al., 2013; Lenton, 2010; Vaughan and Lenton, 2011), large uncertainties remain not only concerning its availability, effectiveness, economic and technological feasibility but also its large-scale environmental consequences (Fuss et al., 2014; Kato and Yamagata, 2014; Smith et al., 2016).

In this study we explicitly do not consider the socioeconomic feasibility of tCDR as a mitigation wedge (Edenhofer and Intergovernmental Panel on Climate Change, 2014; Fuss et al., 2014; Lomax et al., 2015) but rather study its effectiveness as a means of delaying progress on unfavourable (i.e. locked-in or only partially mitigated) emission trajectories. Based on simulations of the carbon sequestration potential of biomass plantations with a state-of-the-art, spatially explicit biogeochemical process model, we demonstrate that even extensive tCDR — if realized around mid-century once the 2°C goal might be crossed —- cannot balance substantial amounts of anthropogenic CO_2 emissions and would be associated with major environmental and societal side-effects.

2.2 Simulation setup

We investigate the ability of tCDR to balance future emissions following two climate scenarios generated to reach specific GMT levels by around year 2100 (Heinke et al., 2013); see Materials & Methods. One scenario is similar to the RCP8.5 storyline (Riahi et al., 2011) in which climate develops on an unabated business-as-usual (BAU) pathway resulting in a GMT rise of ∼4.5°C and 2085 GtC accumulated anthropogenic emissions by 2100 and a crossing of the 2°C threshold around year 2050 (see Materials & Methods). The other scenario is comparable to the RCP4.5 storyline (Thomson et al., 2011) in which current mitigation pledges of the Paris accord are strictly fulfilled (Jeffery et al., 2015) but subsequently not sufficiently increased, leading to a GMT rise of ∼2.5°C and 1227 GtC accumulated anthropogenic emissions by 2100 (and ∼1.8°C around 2050) — still more than the internationally agreed objective.

Our analysis is based on global-scale simulations with the LPJmL Dynamic Global Vegetation Model (Fig. 2.1A,B; for details see Materials & Methods and Supplementary Information (SI) A.1). This well-established model computes the growth and productivity of natural vegetation (Sitch et al., 2003), agricultural crops (Bondeau et al., 2007; Fader et al., 2010) and woody and herbaceous biomass plantations (Beringer et al., 2011), evaluating the climate-dependent transient dynamics of carbon fixation, allocation, turnover and loss in vegetation growth while accounting for interactive effects of soil moisture and atmospheric CO_2 content. Simulations of dedicated biomass-producing plantations differ from those of corresponding natural vegetation by assuming higher productivity and harvest at regular or growth-dependent intervals. A comparison of the simulated woody and herbaceous plantation productivity with observations from field data (Fig. 2.1C) verifies that our results capture a realistic magnitude of production (after Heck et al., 2016).

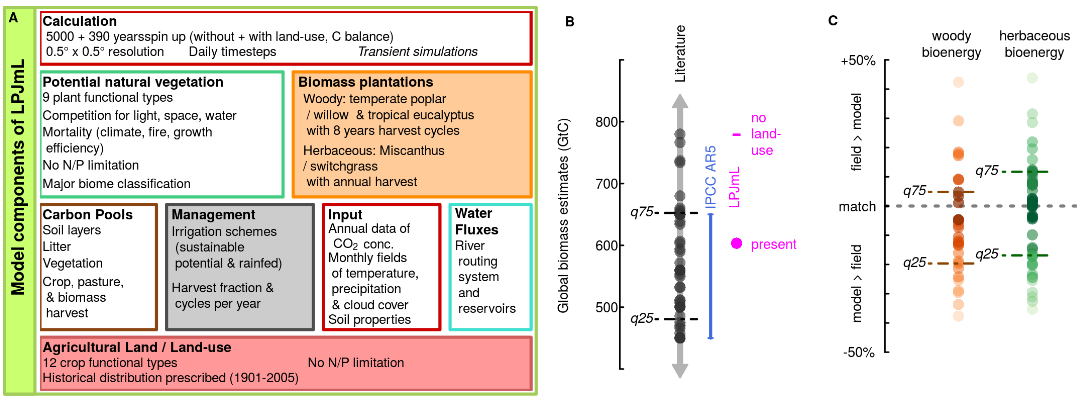

Figure 2.1: Presentation of the LPJmL biosphere model. (A) Overview of model components; (B) model performance in terms of simulated current global living biomass (GtC, 1995–2005 average) with and without land use compared to values found in literature and the IPCC (Table ??); (C) Deviation of simulated yields from woody and herbaceous biomass plantations from field data (%, with 25 and 75 quantiles indicated; Table A.2 after Heck et al., 2016). Note that field plots are small and cultivated under highly artificial growing conditions, specific characteristics of which are not represented in our global model.

We investigate a range of scenarios differing in terms of the spatial extent of tCDR plantations and in terms of whether currently cultivated or uncultivated areas are considered for conversion (Fig. 2.2, Table 1). Replacing all arable natural land (7.4 Gha globally) or all present-day agricultural land (4.2 Gha) places theoretical upper limits on tCDR potentials. Scenarios in which 25% of either natural or agricultural land are converted are less comprehensive but still extensive (3.3 or 2.2 Gha); and conversion of 10% of areas approaches perhaps more realistic but still very ambitious scenarios (1.4 and 1.1 Gha, respectively). Throughout this study we assume that carbon leakage due to losses during biomass harvest, its subsequent transportation, processing and storage amounts to a 50% backflow of carbon to the atmosphere (Lenton, 2010; Powell and Lenton, 2012; Smith et al., 2013b). The remaining harvested carbon is assumed to be immobilized indefinitely and hence removed from the carbon cycle. The replacement of natural vegetation in land conversion is treated equivalently as a one-time harvest with a 50% capture rate.

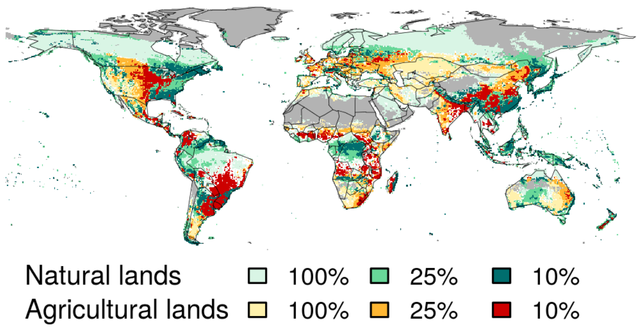

Figure 2.2: Areas considered for tCDR in the studied conversion scenarios. Values are given as % fraction of 0.5 x 0.5° grid cells for scenarios listed in Table 1. Note that only the dominant fraction of either natural or agricultural land in each cell is displayed.

2.3 CO_2 removal potentials of tCDR and associated delays in progress on emissions pathways

We find for an upper ceiling that replacing all ice-free and arable natural land (7.4 Gha) could, by 2100, balance carbon emissions equivalent to the last 67 years of the century (1424 GtC) on the BAU trajectory (Fig. 2.3A). However, while maintaining current global land use patterns for agriculture, the majority of natural ecosystems would be eliminated in such a scenario. Moreover, this upper ceiling of tCDR potentials would be reduced by up to 20% if half of the carbon contained in the natural vegetation converted to tCDR were not extracted and permanently sequestered after clearance. Rededicating instead all cropland and pastures (4.3 Gha, Fig. 2.3B) to tCDR while safeguarding natural ecosystems would achieve a corresponding delay of progression on the BAU pathway of 28 years (705 GtC) but would imply that all land-based food and fiber production is abandoned.

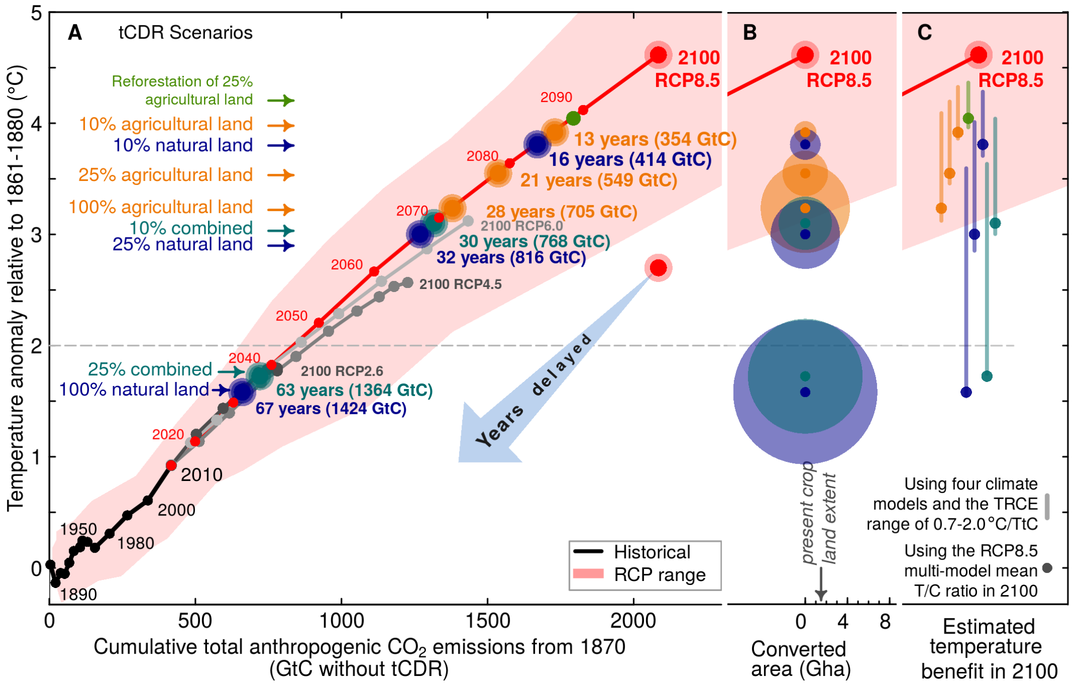

Figure 2.3: Potentials of tCDR along the RCP8.5 trajectory for different biomass plantations scenarios. (A) Potentials in terms of carbon extracted (GtC) and years delayed (dots, indicating how many years of emissions are 'saved' in the respective scenarios compared to the RCP8.5's year 2100 value). (B) Corresponding size of converted area for each tCDR scenario. (C) Estimated GMT changes displayed as a range across four climate models using the very likely range of transient response to cumulative emissions (TRCE) of 0.7–2.0°C per trillion tons of carbon (TtC, Gillett et al., 2013). The dots represent results for tCDR potentials using the temperature-to-carbon (T/C) ratio of RCP8.5 in 2100 (see Materials & Methods). Exact end-point values for each scenario are listed in Table 1. (Adapted Figure SPM.10 from the IPCC AR5 Summary for Policymakers, Stocker et al., 2013b with permission of WG1 TSU).

In scenarios assuming conversion of only a quarter of either agricultural or natural land to tCDR plantations, the sequestered carbon amount is equivalent to a delay of RCP8.5's end-of-century carbon budget by two to three decades (549 GtC and 816 GtC, respectively). Converting 10% of agricultural or natural land (1078 or 1470 Mha), a spatially still extensive but perhaps more realistic scenario similar to the extent considered in RCP4.5 for abandoned land (954 Mha, Thomson et al., 2011), accumulates a biomass harvest that corresponds to 13–16 years of emissions (354 and 414 GtC, respectively) – a small fraction of the 2085 GtC accumulated total anthropogenic emissions reached in 2100 in the BAU scenario (Fig. 2.3A).

Applying the same scenarios on the RCP4.5-like emissions and climate trajectory, we find that despite a weaker CO_2 'fertilization' effect on plant growth (17–20% lower sequestration potentials; Fig. A2), tCDR would be more effective in terms of balancing the further emissions compared to RCP8.5 (Fig. 2.4). As 858 GtC less have to be accounted for, the achievable time delay is a factor of three to four larger (see Tables **??**A and supplementary information SI A.3 for all results). tCDR in such a scenario would therefore indeed be more of a means of averting overly rapid climate warming under pathway lock-in. The 10% conversion scenarios on the RCP4.5 pathway would delay global warming by an equivalent of 41–44 years, which would buy important time but is still not a very long period in view of long-term climate change and the magnitude of environmental consequences incurred (see below).

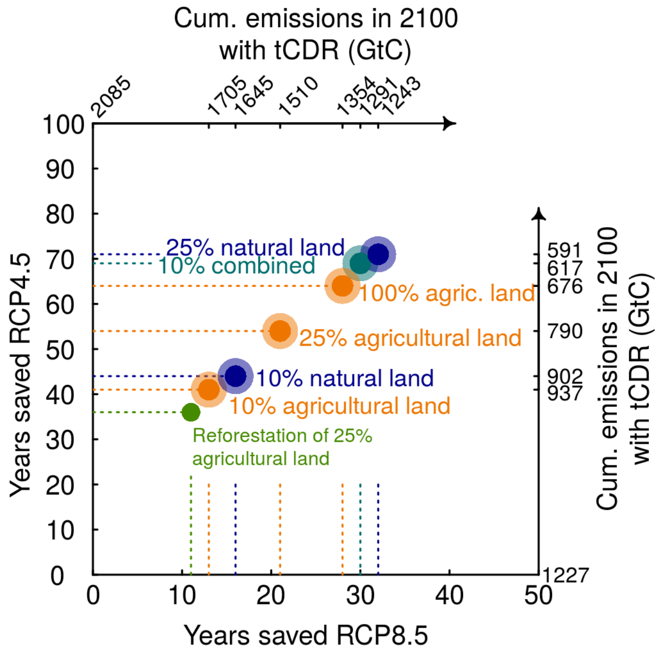

Figure 2.4: Comparison of years delayed and resulting cumulative emissions along an RCP8.5 and an RCP4.5 emission trajectory. In both cases, biomass plantations are assumed to be cultivated as soon as a GMT rise of 2°C is reached on a RCP8.5 trajectory around mid-century and simulated to be operated until 2100.

To shed light on the importance of plantation type and locations, we analyse three additional cases of specific interest under the BAU trajectory (Table 1, Table A.4). The first is simply allowing re-growth of natural vegetation on 25% of agricultural land rather than installing tCDR plantations (Fig. 2.3, green dot; Table 1A). The resulting carbon extraction (291 GtC) is about 60% smaller than if managed plantations were established. Second, we analyse a scenario in which the dedicated bioenergy areas of the IPCC's RCP2.6 scenario (van Vuuren et al., 2011b) and RCP4.5's abandoned agricultural areas

(Thomson et al., 2011)(are jointly replaced by tCDR plantations (Table 1A). Although both scenarios cover large areas, they are not located in the most preferable places for tCDR from a carbon budget point of view, leading to a sequestration of 308 GtC (11 years). Third, we study a scenario in which tCDR is implemented on 25% of agricultural areas but with a focus on maximising the volume of biomass extraction rather than on the optimisation of the overall carbon balance (Fig. A3), for example to serve a future biomass-focused economy. The carbon extraction achieved (466 GtC) is less than if biomass plantations were established according to the largest benefit to the carbon balance, due to the implied negligence of the emissions resulting from land conversion itself (83 GtC if 25% of agricultural areas were rededicated to tCDR).

2.4 Side-effects of large-scale tCDR plantations

Irrespective of the underlying emissions scenario, the scenarios of decelerating cumulative CO_2 emissions through large-scale tCDR deployment would be associated with impacts that likely are ecologically intolerable and socially unacceptable (Table 1B). Converting 25% of the most productive natural areas to tCDR plantations implies widespread loss of habitats, reducing biodiversity and modifying ecosystems which are already under pressure (Ostberg et al., 2015; Steffen et al., 2015) and face severe risks of change under climate warming (Ostberg et al., 2013; Warszawski et al., 2014). The global forest extent, currently estimated at 62% of natural forest remaining (Steffen et al., 2015), would be halved in this tCDR scenario. When converting 10% of natural land, still almost 1.4 Gha of habitats would be lost or degraded – an area corresponding to half of today's cropland extent.

From calculating the nitrogen content in the globally harvested biomass under BAU conditions, we find that biomass harvest would extract 96–151 TgN yr^{-1} on 10–25% of the agricultural area (in addition to the demand on the remaining cropland). This is of a magnitude comparable to today's worldwide nitrogen demand of 147 TgN yr^{-1} in 2014 (Steffen et al., 2015; FAO, 2015) which already has led to transgression of the suggested "planetary boundary" for nitrogen by a factor of two (Steffen et al., 2015; FAO, 2015) and would additionally release substantial amounts of non- CO_2 greenhouse gases into the atmosphere.

Agricultural calories production on cropland would be reduced by 73% (43%) when converting the most suitable 25% (10%) of cropland for the purpose of tCDR. In a world inhabited by at least 9 billion people in 2050 it is unlikely that such deficits could be overcome by management intensification or improvement (Bajželj et al., 2014).

Transforming merely all pastures (i.e. keeping all cropland while eliminating all range-based meat and dairy products, Table 1A) would not result in substantial climate benefits: while pastures are more extensive than croplands they are also less productive for tCDR plantations.

2.5 GMT reduction potentials of tCDR

We stress that our simulations do not imply an alteration of emissions, which are given by a scenario of lock-in into a particular emissions trajectory due to infrastructural, economic or political factors, but a delay in their progression. The associated delay in GMT warming cannot be directly computed in the absence of fully-coupled biosphere-atmosphere dynamics in our model. However, assuming that biogeophysical feedbacks were of secondary order (Brovkin et al., 2013; Gillett et al., 2013), it may be approximated from the near-linear relationship between cumulative emissions and transient GMT change (see Materials & Methods). We find that the delay in progression on the emissions trajectory in the year 2100 amounts to lowering unabated RCP8.5 GMT increase by 1.6–3.1°C in the most extensive tCDR, providing a purely theoretical upper ceiling, and by 0.8–1.8°C in the 25% and 10% conversion cases, respectively deployment (Fig. 2.3B and C). Considering merely these orders of magnitude, and neglecting whole-system feedbacks, these numbers indicate that the theoretical upper ceiling of biogeochemical tCDR is just large enough to potentially restore a 2°C target by 2100. The still immensely land-consuming but less comprehensive cases indicate qualitatively that a 2°C objective could not be restored by tCDR alone. What is more, our analysis of surface albedo changes in response to the implementation of biomass plantation (see Materials & Methods) suggests a local warming on previous cropland or pasture due to increased surface reflectivity which, however, is very sensitive to e.g. the original land cover, crop management, snow cover and model parameterizations (see SI A.1). Fully coupled simulations are needed to assess such climate feedbacks from biogeophysical and also biogeochemical changes (e.g. including changing atmospheric CO_2 concentrations and ocean responses (Zickfeld et al., 2013; Tokarska and Zickfeld, 2015), which currently cannot be accomplished because Earth system models lack a process-based implementation of tCDR plantations as available in LPJmL.

2.6 Conclusion

We conclude that tCDR does not offer a late-regrets "climate emergency" service in the case of failed mitigation leading to unabated continuation of emissions. Substantial post-factum carbon removal from the atmosphere would require utilising a major fraction of the global land surface (natural or agricultural areas), with intolerable large environmental and social costs. More realistic, i.e. spatially less extensive scenarios (requiring conversion of 10% of natural or agricultural land), on the other hand, would delay accumulation of emissions on a BAU pathway by not more than a decade. Even in scenarios with simultaneous emission reductions (RCP4.5) the potentials are limited to around 40 years but with similar environmental costs. What is more, likely increasing competition for land and water, the effects of climate change on agricultural production and the disparate economic and technological feasibility of tCDR make our biogeochemical quantifications of tCDR potentials rather optimistic estimates. Hence, tCDR is neither a „green" option for climate engineering (Heck et al., 2016) nor, within this century, a realistic "emergency" option to counteract anthropogenic greenhouse gas emissions. Mitigating anthropogenic emissions early and effectively is a far more tractable option for limiting global warming (Luderer et al., 2013; Smith et al., 2016).

Table 2.1: Potentials and impacts for each tCDR scenario. (A) Description of the tCDR scenarios and their potentials in 2100 in terms of carbon extraction (GtC) and net flux (GtC yr^{-1}), years of emissions delayed and GMT change using the multi-model T/C ratio in 2100 (°C) for a business-as-usual pathway RCP8.5 and a mitigation pathway RCP4.5 (detailed results for the latter can be found in Table A.3); (B) The impacts of tCDR on land conversion (Mha) and remaining forest extent (reforestation potential), food production (% loss of kcal cap^{-1} day^{-1} production) and estimated nitrogen application (Mt yr^{-1} and kg ha^{-1} yr^{-1}).

		Implication	(A) Potentials in 2100				(B) Impacts			
			C extracted (GtC)	C flux (GtC yr^{-1}, mean)	Years delayed (yrs)	T change (°C)	Area converted (Mha)	Forest extent remaining (%)	Kcal loss (%)	N application in total (Mt yr^{-1}) & per ha (kg ha^{-1} yr^{-1})
RCP8.5		Business as usual with high emissions	-2085	26	-	4.6 (since 1870)	-	62[1]	-	147[2] - 150[1]
Agricultural land	100%	Limited to no food production	705	12	-28	-1.6	4267	100	100	196, 46
	25%		549	9	-21	-1.2	2176	(85)	73	151, 132
	10%		354	6	-13	-0.8	1078	(73)	43	96, 187
Natural land	100%	Drastic reductions to total loss of natural ecosystems	1424	25	-67	-3.1	6899	0	-	570, 55
	25%		816	14	-32	-1.8	3307	30	-	328, 91
	10%		414	7	-16	-0.9	1470	49	-	160, 106

[1] Steffen et al. (2015) and [2] FAO (2015)

* Table continued on next page.

*Continued table 2.1

		Implication	**(A) Potentials in 2100**				**(B) Impacts**			
			C extracted (GtC)	C flux (GtC yr^{-1}, mean)	Years delayed (yrs)	T change (°C)	Area converted (Mha)	Forest extent remaining (%)	Kcal loss (%)	N application in total (Mt yr^{-1}) & per ha (kg ha^{-1} yr^{-1})
Special cases	RCP2.6 + RCP4.5	Dedicated bioenergy + abandoned lands	308	5	-11	-0.7	1355	57	15	96, 275
	25% agric. with NV	Restoration of land with natural vegetation	291	4	-11	-0.6	2151	-	-	-
	25% agric. chosen by highest harvest	Disregard of carbon emission	466	8	-18	-1.0	1950	-	-	-
	100% pastures	No meat or dairy production	391	6	-15	-0.9	2771	-	-	-
RCP4.5		Afforestation, reduced emissions	-1227	5	-	2.6	-	-	-	-
Agric. land	25%		436	7	-54	-0.9	-	-	-	-
Natural land	25%		631	11	-72	-1.3	-	-	-	-

Acknowledgements

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Author contributions: WL and LB designed the study. VH collected literature data on field studies of biomass plantations and provided the validation analysis. LB carried out and post-processed simulations with LPJmL, analyzed the results and created all figures. LB led the writing process with input from WL, DG and VH. We deeply thank H.-J. Schellnhuber for his support and thoughts on this study.

Statement on competing interest: the authors declare that they have no competing interests.

Materials and methods

LPJmL model

We here use the well-established Dynamic Global Vegetation Model including managed land, LPJmL (Sitch et al., 2003; Bondeau et al., 2007) to simulate the growth of natural and agricultural vegetation – including biomass plantations – and the associated biogeochemical processes in a single, internally consistent framework. As shown in Fig. 2.1A, LPJmL represents nine plant functional types (dynamic distribution based on bioclimatic conditions and competition for light, water and space), 12 crop functional types (prescribed distribution and management with calibrated yields; Fader et al., 2010) and pastures, as well as two second-generation bioenergy functional types (prescribed distribution in scenarios as specified in Table 1, uncalibrated yields). Calculation of the transient simulations is done on a daily time step and on a 0.5 x 0.5° grid. Bioenergy plantations are either woody (representing the growth characteristics of temperate willows and poplars or tropical Eucalyptus) or herbaceous (imitating Miscanthus and switchgrass) with harvest cycles of eight years or multi-annual occurrences, respectively (Beringer et al., 2011). The performance of simulated, non-calibrated bioenergy harvests has been compared to current field studies as shown in Fig. 2.1C and by Heck et al. (2016). For detailed description please refer to the SI A.1.

Land use scenarios (tCDR)

For the simulations of tCDR potentials, we selected and replaced either all, 25%, or 10% of all 0.5° grid cells by woody or herbaceous biomass plantations, on currently natural (e.g. parts of five major biomes) or agricultural areas (e.g. parts of cropland and pastures) or an equal mixture of both – see Table 1. Non-arable grid cells, e.g. those covered by ice, snow or desert, were excluded. Grid cells and plantation types are selected for conversion such that the highest global net carbon potential is achieved in each scenario (global distribution shown in Fig. A1), taking into account carbon losses due to the conversion itself and carbon captured in 50% of the harvested biomass (Fig. 2.2 and SI A.2).

Calculation of carbon and global temperature potentials

For each scenario of tCDR deployment we compute the carbon extraction from the atmosphere as change in carbon stored in the land carbon pool and in the accumulated biomass harvest. Following the cumulative carbon emissions of RCP8.5 (Meinshausen et al., 2011), the 2°C target is crossed around 2050 (for a detailed description, please see SI A.2) and 4.5°C of warming reached in 2100 – defining the simulation period of our study. For RCP4.5, which reaches 1.8°C and 2.5°C of warming are around mid-century and 2100, respectively, simulations were also carried out for that period. Climate forcing and atmospheric CO_2 concentrations were taken from the MPI-ESM ECHAM5 model whose biomass response in LPJmL resides in the middle of responses to different CMIP3 climate models (Fig. A4, Heinke et al., 2013).

We apply the multi-model mean temperature-to-carbon ratio (T/C ratio) of RCP8.5 in 2100 (Stocker et al., 2013b) to our carbon sequestration potentials to estimate the possible GMT reduction from tCDR alone in 2100 (Fig. 2.3C, dots). This procedure is similar to the application of the transient response to cumulative emissions (TRCE, Gillett et al., 2013) which is estimated to lie between 0.7–2.0°C/TtC (°C per trillion tons of carbon) and which, multiplied with land carbon changes simulated in our study, serves as a good approximation of GMT change. The TRCE approach does not capture nonlinear feedbacks due to land use or land cover change (e.g. biogeophysical effects; Brovkin et al., 2013; Boysen et al., 2014. Albedo changes due to tCDR are calculated by the model (Forkel et al., 2014) to be similar magnitude but opposite sign as caused by historical land-use changes (Pongratz et al., 2011) on agricultural lands likely leading to a warming effect (note, that recent studies differ in this finding, see SI A.1). Contrarily, the conversion of natural land would increase the albedo, possibly leading to a cooling effect, especially as evaporative fluxes tend to increase (see SI). The ocean response is assumed to be included in the interactively simulated climate forcing (note that atmospheric CO_2 concentrations are not altered in our study). Carbon and temperature potentials for four different climate models are shown as vertical bars in Fig. 2.3C (see also Fig. A4).

Impacts of tCDR

We here calculate impacts of tCDR on food production, forest extent and the nitrogen cycle. Avoiding speculations about future food, diet and population development, we calculate the drawbacks on today's per capita daily calorie production. The calibrated crop yields in LPJmL reach a crop production of 3,038 kcal cap^{-1}day^{-1} for 7bn people.

The risk of transgressing the planetary boundary for land-system change is determined by the remaining forest extent. We adapted this approach according to the fractional forest areas provided by LPJmL which partly differ from those used in Steffen et al. (2015). Scaling our potential forest extents to those in Steffen et al. (2015), we could analyse the relative change of area in our scenarios and calculate the position with respect to the planetary boundary for land-system change.

Nitrogen limitation to plant growth is not explicitly modelled in LPJmL. Therefore, we did a post hoc estimation of the nitrogen content in the harvested and removed biomass which can be translated to the required amount of nitrogen fertilization (which could also partially be added by nitrogen depletion). For the applied nitrogen contents of woody and herbaceous biomass plantations, see the SI A.3.

3 Impacts devalue the potential of large-scale terrestrial CO_2 removal through biomass plantations[1]

[1]This chapter is published with minor modifications as: L. Boysen, W. Lucht, and D. Gerten and V. Heck (2016). “Impacts devalue the potential of large-scale terrestrial CO2 removal through biomass plantations”. *Environmental Research Letters*. DOI:10.1088/1748-9326/11/9/095010.

Abstract

Large-scale biomass plantations are often considered a feasible and safe climate engineering proposal for extracting carbon from the atmosphere and, thereby, reducing global mean temperatures. However, the capacity of such terrestrial carbon dioxide removal (tCDR) strategies and their larger Earth system impacts remain to be comprehensively studied — even more so under higher carbon emissions and progressing climate change. Here, we use a spatially explicit process-based biosphere model to systematically quantify the potentials and trade-offs of a range of biomass plantation scenarios dedicated to tCDR, representing different assumptions about which areas are convertible. Based on a moderate CO_2 concentration pathway resulting in a global mean warming of 2.5°C above preindustrial level by the end of this century — similar to the Representative Concentration Pathway (RCP) 4.5 — we assume tCDR to be implemented when a warming of 1.5°C is reached in year 2038. Our results show that biomass plantations can slow down the progression of increasing cumulative carbon in the atmosphere only sufficiently if emissions are reduced simultaneously like in the underlying RCP4.5 trajectory. The potential of tCDR to balance additional, unabated emissions leading towards a business-as-usual pathway alike RCP8.5 is therefore very limited. Furthermore, in the required large-scale applications, these plantations would induce significant trade-offs with food production and biodiversity and exert impacts on forest extent, biogeochemical cycles and biogeophysical properties.

3.1 Introduction

Terrestrial carbon dioxide removal (tCDR) strategies, as part of a suggested climate engineering (CE) portfolio (Vaughan and Lenton, 2011), aim at extraction of CO_2 out of the atmosphere in the process of carbon fixation by plants through photosynthesis. Amongst other CE ideas that intentionally alter the radiative forcing of the atmosphere, tCDR is rated as a relatively “safe” technology with medium carbon removal potentials at low economic costs (Shepherd, 2009). However, efficient tCDR requires large-scale biomass plantations (BPs) or afforestation projects, long implementation periods (Vaughan and Lenton, 2011; Caldeira et al., 2013) and suitable utilization pathways of the allocated biomass to permanently extract as much carbon as possible (Klein et al., 2014a).

Recent studies (Humpenöder et al., 2014; Humpenöder et al., 2015; Lomax et al., 2015) see global re- and afforestation initiatives as well as managed biomass plantations, combined with suitable conversion pathways (e.g. bioenergy with carbon capture and storage, BECCS), as an important component of the mitigation portfolio. This view is supported by the Summary for Policymakers of Working Group I of the International Panel on Climate Change's Assessment Report 5 (Stocker et al., 2013b) in which only the trajectory RCP2.6 (van Vuuren et al., 2011b) trajectory stays below the 2°C target for global mean temperature (GMT) rise due to the assumed extensive use of BECCS, whereas the other RCPs imply less or no mitigation based on BPs. Other analyses suggest that this ambitious mitigation pathway is not reliable due to uncertainties in high biomass feedstock supply (Kato and Yamagata, 2014), carbon cycle dynamics, technologies and political frameworks (Fuss et al., 2014).

CE projects are generally being suggested for deployment in the later decades of this century when consequences of unabated global warming might become intolerable for ecosystems and human well-being (Gerten et al., 2013; Piontek et al., 2014). For example, there is consensus that the 2°C or 1.5°C target will be out of reach if rapid mitigation efforts in the near future fail (Bertram et al., 2015; Luderer et al., 2013; Rogelj et al., 2015c). But so far research is lacking quantitative studies on the potential and consequences of later deployment of large-scale BPs as a CE rather than a mitigation method. For example, the deployment of tCDR could be suggested to lower the estimated median change in GMT of 2.7°C in 2100 as anticipated by the currently pledged so-called intended nationally determined contributions (INDCs, Jeffery et al., 2015) to 1.5°C by 2100 once all near-term efforts will have been exhausted. To date, only a few studies contextualize tCDR explicitly as a CE option (Lenton, 2010; Vaughan and Lenton, 2011; Caldeira et al., 2013) but their results are based on global estimates of available area and conversion pathways (i.e. not spatially explicit and without support by sound modeling of involved biogeochemical processes).

Our study focuses on the potentials and trade-offs of tCDR in a climate similar to that in RCP4.5 with a GMT rise of 2.5°C by 2100 (Heinke et al., 2013) and similar to the anticipated warming according to the submitted INDCs (Jeffery et al., 2015). So far, these mitigation pledges still fail to limit GMT rise to 2°C or even 1.5°C by the end of the century. In this study we therefore assume a deployment of tCDR with the intention to postpone or counter further emissions once the 1.5°C target will be reached around 2038 (with ca. 660 GtC of cumulative emissions) using a spatially explicit systematic modeling framework. We create land-use scenarios in which the climatically and biogeochemically most suitable areas for tCDR are either converted to highly productive BPs or natural vegetation (NV). Specifically we answer the three following research questions:

1. Could tCDR substantially delay the progression of cumulative emissions once a GMT rise by 1.5°C is reached in a partial mitigation scenario like RCP4.5?
2. Could tCDR, deployed at a time when climate projections strongly diverge, even balance additional emissions towards a business-as-usual level of emissions (akin to RCP8.5)?
3. What would be some of the non-economic costs of the required excessive land-use and land cover changes for ecosystems and human well-being (e.g. effects on food production, forest extent and biogeochemical flows)?

3.2 Materials and methods

3.2.1 The biosphere model LPJmL

We created land-use scenarios of large-scale tCDR for evaluation with the Dynamic Global Vegetation Model LPJmL (Bondeau et al., 2007; Schaphoff et al., 2013) on a 0.5 degree x 0.5 degree global grid. The model was driven by monthly observational fields of temperature, precipitation and cloudiness as well as by annual CO_2 concentrations for the historic period of 1901 to 2005 as described in Ostberg et al. (2015). The model dynamically simulates the biogeographical distribution of nine natural plant functional types depending on light, water and competition. Land-use patterns for 12 crop types and pasture were prescribed from 1901 to 2005 following transient historical changes (Fader et al., 2010) up to the year 2005 including irrigated areas (Portmann et al., 2010; Jägermeyr et al., 2015). Crop yields are calibrated to match national FAO statistics as described in Fader et al. (2010). To achieve soil carbon equilibrium and distributions of natural vegetation, the model was spun up for 5000 years without land-use but under the repeated climate of the years 1901-1930 (Schaphoff et al., 2013). A subsequent spin-up of 390 years accounted for the influence of land-use changes on the carbon balance.

From 2005 on, we prescribed a climate forcing arriving at 2.5°C of mean global warming in 2100 (Heinke et al., 2013), similar to the CO_2 trajectory of RCP4.5. We used climate model output (e.g. precipitation patterns, temperature, wet days, cloudiness and CO_2 concentration) from MPI-ESM simulations prepared for the CMIP3 framework, which lies in the middle range of climate models considered in Heinke et al. (2013).

Crop and pasture spatial patterns were kept constant between 2005 and 2038, the year in which the 1.5°C target is crossed in our climate scenario. We assumed that in that year selected land areas would be converted to BPs following the framework of table 3.1 (see next section). Bioenergy trees (BT) are simulated to meet the growth characteristics of poplar and willow in temperate regions and *Eucalyptus* in tropical areas. Bioenergy grasses (BG) imitate the growth behaviour of *Miscanthus* and switchgrass. BT are simulated to be initially cultivated from small saplings on the field which grow for eight years when they are partially harvested down to their stump with rapid regrowth due to the remaining root system. Plantations are clear-cut and replanted after five harvest cycles (i.e. 40 years). Contrarily, BG grow much faster and 85% of the above ground biomass can be harvested once at the end of the growing season or several times a year as soon as leaf mass reaches 400 g m^{-2}. These parameter settings for both, BT and BG are chosen and tested to represent good global matches with reported yields on field as described by Heck et al. (2016). Here, we consider only non-irrigated bioenergy plants. The global distribution of BG and BT in the different tCDR scenarios depends on the highest net accumulated biomass harvest as well as on changes in land carbon pools in each grid cell (SIB.1 Fig. B1). For example, the soil carbon allocation of BT can be more beneficial for the net carbon sequestration than higher harvest rates of BG in some regions which is why BT would be planted in there. This procedure mainly allocates BG in tropical and temperate regions and BT in high latitudes and water stressed tropical regions where the deeper root system of BT are preferential over BG.

Simulated yields of herbaceous and woody bioenergy plants (Beringer et al., 2011) were recently evaluated against field studies (Heck et al., 2016). The hydrological, agricultural and biogeochemical simulations of LPJmL were thoroughly evaluated and validated in previous studies (Bondeau et al., 2007; Rost et al., 2008; Fader et al., 2010; Schaphoff et al., 2013).

3.2.2 Scenarios of tCDR areas

In our baseline scenarios (table 3.1), either all, a quarter or 10% of the grid cells on agricultural (AGR) or arable (e.g. ice, snow and desert-free) natural land (NAT) were assumed to be converted to BPs to cover the range from maximum to more feasible, yet lower potentials (figure 3.1). To avoid the conversion of solely highly productive rainforest, five major biomes were considered separately for tCDR (tropical, temperate and boreal forest as well as grassland and tundra). Similarly, both cropland and pastures were treated equally to avoid judgment about which of these land use types to convert preferentially.

In an alternative setup, we modified these scenarios by selecting the grid cells with highest biomass harvest only, without considering the land carbon changes through

Table 3.1: Scenario definitions, areas covered, and qualitative implications of their implementation.

Scenario	Name	Choice of cells	Area (Mha)	Implication
	LUconst	Constant land-use patterns of 2005	4267	Today's food production
Natural land	100NAT	All arable cells	6883	Severe elimination or reduction of ecosystems / biodiversity
	25NAT	The 25% most productive cells	3245	
	10NAT	The 10% most productive cells	1431	
Agricultural land	100AGR	All cells	4267	No or strong reduction in food production (both crop & pasture land)
	25AGR	The 25% most productive cells	2104	
	10AGR	The 10% most productive cells	1045	
RCP	RCP2.6	van Vuuren et al. (2011b)	445	Bioenergy on cropland in 2100
	RCP4.5	Thomson et al. (2011)	954	Afforestation of 468 Mha cropland and 486 Mha pastures in 2100

conversion from previous use during the process of selecting grid cells. This allows an analysis of the impact of land conversion emissions on the overall climate potential of tCDR. Furthermore, we compare our results of highly managed biomass plantations to the potentials of (regrowing) natural vegetation (NV) on the same chosen areas as in our baseline scenarios.

We here explicitly aim at the maximised possible biophysical potentials and therefore neglect limitations on land-use and land cover transitions through social, economic or political restrictions.

3.2.3 Calculation of carbon potentials and years delayed

All simulation results, such as carbon pools (vegetation, litter and soil) and accumulated biomass harvests, were smoothed using a 10-year or 16-year moving average (depending

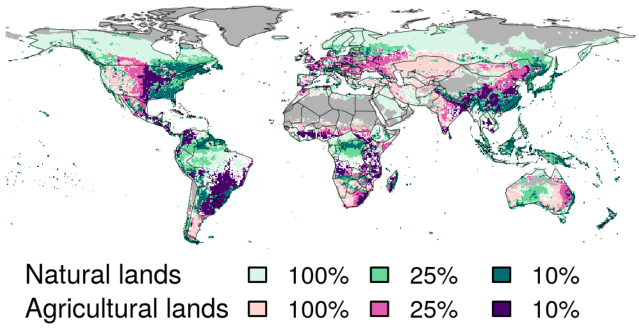

Figure 3.1: Spatial coverage of tCDR scenario on natural (green) and agricultural (pink) areas according to table 3.1.

on the harvest cycle) up to around year 2100 for herbaceous or woody BPs, respectively. We assumed a 50% capture rate of the carbon stored in the biomass harvest with a back-flow of the other half to the atmosphere due to harvest losses, conversion inefficiencies and leakage rates (Lenton, 2010; Powell and Lenton, 2012; Smith et al., 2013b). Consideration of more detailed and complex conversion pathways or fossil fuel substitutions (Gilbert and Sovacool, 2015) are beyond the scope of this study and thus, the tCDR potentials found here are pure carbon extractions to an unlimited storage capacity, reduced by the leakage. The same strategy is applied to the conversion of natural land by treating the replaced biomass as one harvest cycle with 50% loss of carbon to the atmosphere.

To calculate the time delay of tCDR on the cumulative emission trajectory, sequestration potentials of our tCDR scenarios were subtracted from the RCP's cumulative emission budget in 2100. We then counted the years until the reduced budget matches the RCP trajectory backwards in time.

3.2.4 Calculation of impacts

Following the definition of the planetary boundary for land-system change (PB-L, Steffen et al., 2015), the loss of forest was estimated for each tCDR scenario and compared to the potential forest extent without human influence. This concept suggests that three major biomes are distinguished: boreal, temperate and tropical forests with boundaries suggesting that 85%, 50% and 85%, of the natural forest are to be preserved, respectively, before leaving the "safe operating space for humanity". At present, the global boundary of 75% of remaining forest extent — the average of the three biome-specific values — is already transgressed (62% of forest still existent). The extent of forested land and land-use areas differs between the dataset used in Steffen et al. (2015) and the simulated extents by LPJmL (Ostberg et al., 2013). For that reason, forest areas in LPJmL were linearly scaled to fit those calculated in Steffen et al. (2015), and the percentage changes were calculated.

Our scenarios affect large areas which would induce biogeophysical effects e.g. if the reflectivity of the surface (albedo α) is changed substantially (Arora et al., 2011). BPs tend to be darker than cropland (competing effects of longer growing season of darker BG on agricultural land versus less dense bright crops revealing darker soils (Davin et al., 2014; DeLucia, 2015; Miller et al., 2015), sparse shrubland or seasonally snow-covered tundra vegetation or cropland, but brighter than dense tropical or temperate forests. To estimate the effect of albedo changes calculated by LPJmL (Forkel et al., 2014, see SIB.2), we compare them to albedo changes caused by historical changes in land-use and land cover (Pongratz et al., 2011). As changes in moisture fluxes could also induce warming or cooling effects through altered latent heat fluxes (Davin et al., 2007), we also compared moisture fluxes of unchanged vegetation and managed land in 2100, too.

By converting the LPJmL-simulated (and calibrated) crop yields to dry matter and applying the nutrition values for each crop type (Wirsenius, 2000), we also calculated the percentage loss of per-capita calorie production for 7bn people in each tCDR scenario affecting agricultural cropland.

LPJmL implicitly assumes optimal nutrient supply to vegetation. Studies argue that fertilizers for BPs are only required during establishment in view of modern management techniques with a natural backflow of nitrogen (N) into the soils (Himken et al., 1997; Brosse et al., 2012). In the absence of long-term studies, we estimated the needed N fertilizer demand based on the removed biomass (C:N ratio). We assumed N contents of both plantation types of 5kgN $t^{-1}C^{-1}$ dry mass (Beringer et al., 2011). With this, we approximated literature values of 4.9 gN kg^{-1} (Pennington, 2012) and 4.8 gN kg^{-1} (Karp and Shield, 2008) for BG and of 5 gN kg^{-1} (Karp and Shield, 2008) for BT. The carbon content of dry matter is approximated with 45% for herbaceous (Kato and Yamagata, 2014) and 50% for woody biomass (Lenton, 2010; Powell and Lenton, 2012).

3.3 Results

3.3.1 The carbon sequestration potentials of tCDR

Figure 3.2 shows that the spatially most extensive, only theoretical scenarios (2.5–7.4 Gha, 100AGR, 25AGR+25NAT, 25NAT, 10AGR+10NAT and 100NAT) could fully compensate for the cumulative emissions on the RCP4.5 trajectory between 2038 and 2100 (i.e. the tCDR trajectories allow for higher sequestration potentials than the ongoing cumulative emissions). This would delay the carbon budget otherwise reached in year 2100 under RCP4.5 of 1227 GtC by 73 years (corresponding to 649 GtC, table 3.2) in the 100AGR scenario (figure 3.2(b)). Even more than 220 years could be balanced in the 100NAT scenario since in such a scenario even more carbon could be extracted than has been emitted since 1880 (1361 GtC). tCDR on smaller, more likely convertible areas of 1.0–2.1 Gha (25AGR, 10NAT, 10AGR) could translate into a postponement of 46–61 years (341–514 GtC). This implies that the maximal permitted amount of emitted carbon to stay below 2°C (ca. 220 GtC from 2038 on in RCP4.5) could just be balanced by the end of this century.

Table 3.2: Potentials of tCDR in year 2100 in terms of carbon extracted (GtC) and years of emissions saved (yrs). All results are based on an RCP4.5-like emission pathway. 25AGR_h refers to the 25AGR scenario chosen by highest harvest only; 25AGR_nv refers to the 25AGR scenario with natural vegetation instead of BPs and 25NAT_nv on the potential of standing natural vegetation on the 25NAT area.

Scenario	C extraction (GtC)	Years delayed (yrs)
100NAT	1361	>220
100AGR	649	73
25NAT	792	88
25AGR	514	61
10NAT	401	51
10AGR	341	46
25AGR_nv	266	39
25NAT_nv	61	12
25AGR_h	502	60
RCP2.6	76	15
RCP4.5	220	34

However, these ambitious sequestration potentials of tCDR would only be sufficient following a RCP4.5 climate trajectory but not under unabated emissions as in RCP8.5.

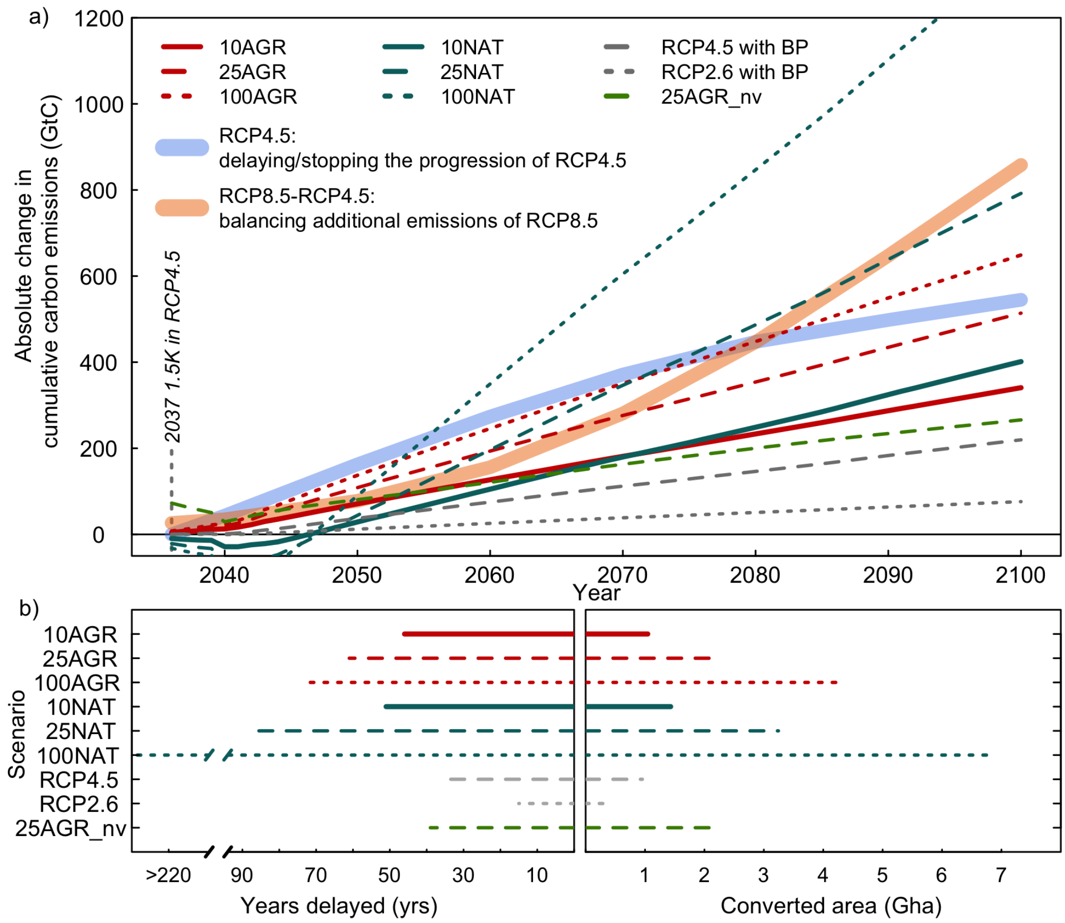

Figure 3.2: The potential of tCDR to delay and balance cumulative emissions once the 1.5°C target is crossed and until 2100. (a) Carbon sequestration potential of tCDR scenarios over time in comparison with cumulative emissions of RCP4.5 and the additional emissions of RCP8.5. (b) Years by which the progression on a RCP4.5 cumulative emission trajectory is delayed and the according area sizes for each scenario.

This becomes clear when looking at the trajectory of additional cumulative emissions (858 GtC more in 2100) leading towards a RCP8.5 pathway (orange line). tCDR could only balance these additional emissions if plantation sizes reached 7.4 Gha on natural land (100NAT with 1361 GtC) or large parts of natural and agricultural land (25AGR+25NAT, 5.4 Gha) would be converted (1306 GtC). All scenarios of a smaller global BP area could only partly balance these additional emissions of a BAU pathway.

The sequestration potential of tCDR after 62 years of operation (2038–2100) highly depends on the plantation size and history of the land being converted. While converted natural areas are much larger than in the AGR scenarios, the carbon loss from soils and biomass partly diminishes the BP sequestration potentials (figure 3.3(a), red lines).

This loss can however be compensated for if 50% of both the replaced natural biomass and the accumulated harvest are accounted for as sequestration potential (figure 3.3(a), red arrows). tCDR on agricultural land (figure 3.3(b), red lines) in contrast increases the small current land carbon stocks (yellow lines) almost as much as if potential natural vegetation was to regrow on these areas (green lines). In both cases, BP harvest overcompensates any conversion losses by far (red arrows).

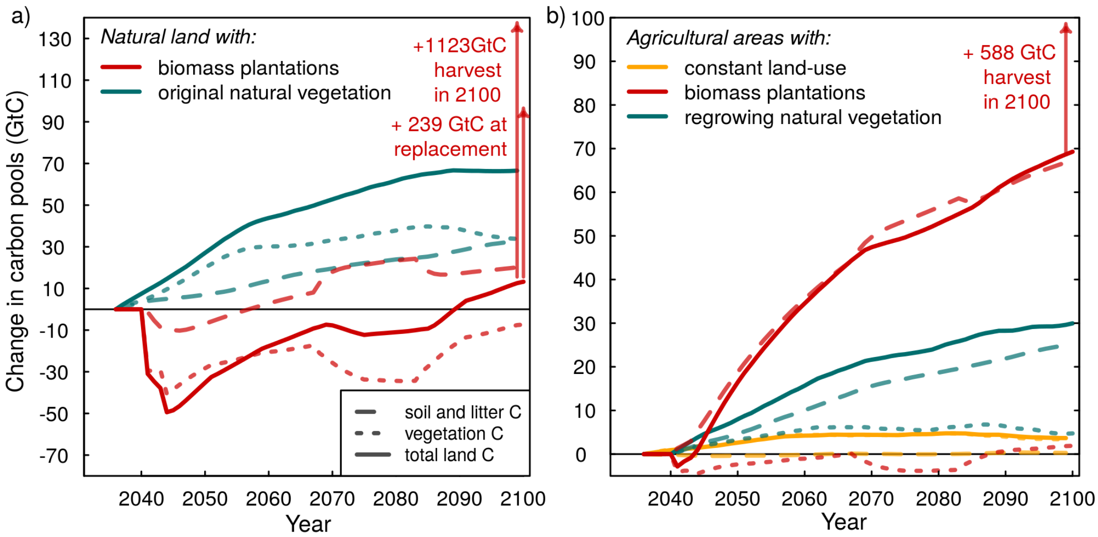

Figure 3.3: Changes in carbon pools if all natural areas (a) were converted to tCDR (red) or agricultural (b) areas were converted to tCDR (red) or NV (green) from 2038 on. The red arrows indicate the magnitude of carbon sequestration due to BP harvests.

A variant of the 25AGR scenario in which afforestation rather than BP is chosen (25AGR_nv; figure 3.2) would sequester 266 GtC until 2100 — almost half the potential of BPs. As shown in figure 3.3(a), the land carbon restoration (i.e. the increase of soil and litter carbon) is also half to that under BPs and the additional BP harvest results in significantly higher potentials than under NV. The standing natural vegetation on the area of the 25NAT (25NAT_nv) scenario would sequester 61 GtC — substantially less than with BPs on this land despite prevented land cover change emissions.

By neglecting land carbon changes while selecting grid cells, the sequestration potential of tCDR is reduced slightly since land conversion emissions diminish parts of the higher harvest potentials, especially on natural land (see supplementary information SI figure B2). This also transfers to the potentials of the dedicated bioenergy areas in RCP2.6 and re- and afforestation areas in RCP4.5 which were chosen by Integrated Assessment Models for agro-economical reasons (figure 3.2(a)). Although the afforestation areas of

RCP4.5 cover a similar area size of agricultural land as the 10CP scenario, the tCDR extraction is 181 GtC smaller. RCP2.6 approximately affects half of the 10AGR area but the sequestration potential is reduced to one fifth.

3.3.2 Impacts of large-scale tCDR implementation

The transformation of land for the purpose of tCDR would have various impacts as qualitatively listed in table 3.1 and quantified here with measures described in table 3.3. Figure 3.4 maps the impacts of converting large-scale areas for tCDR on albedo changes, food production, forest extent and biodiversity.

Table 3.3: Impacts of tCDR on the remaining natural forest extent (%), the planetary boundary for land-system change (PB-L), global kilocalorie production (%) and nitrogen application (Mt yr^{-1} and, respectively, kg $ha^{-1}yr^{-1}$) in 2100.

Scenario	Remaining natural forest	Risk of transgressing PB-L*	Change in kcal $cap^{-1}day^{-1}$ (%)	Total N application (Mt yr^{-1})	N application ($kg\ ha^{-1}yr^{-1}$)
100NAT	0	High	–	589	57
25NAT	31	High	–	345	99
10NAT	49	High	–	169	114
100AGR	(100)	(Safe)	-100	200	47
25AGR	(85)	(Safe)	-73	160	126
10AGR	(73)	(Incr.)	-43	108	181

*Note on PB-L: high refers to beyond the uncertainty zone, safe refers to within the safe operating space and increasing (incr.) refers to beyond planetary boundary but within the uncertainty zone. Brackets indicate a possible increase of forest extent if BPs were assumed to be semi-natural vegetation.

Biogeophysical effects of large-scale land conversions to BPs could decrease possible GMT reductions because albedo effects may cause local warming. By comparing albedo (α) values of original and BP land cover (figure 3.4(a)), we find that converting pastures and cropland could generally induce a positive radiative forcing which is likely stronger than the induced reduction in radiative forcing due to historical land use and land cover changes (Pongratz et al., 2011). Converting natural vegetation to BPs would likely increase the reflectivity resulting in a local cooling. We find that moisture fluxes could even be enhanced, leading to additional cooling effects through increased evaporation

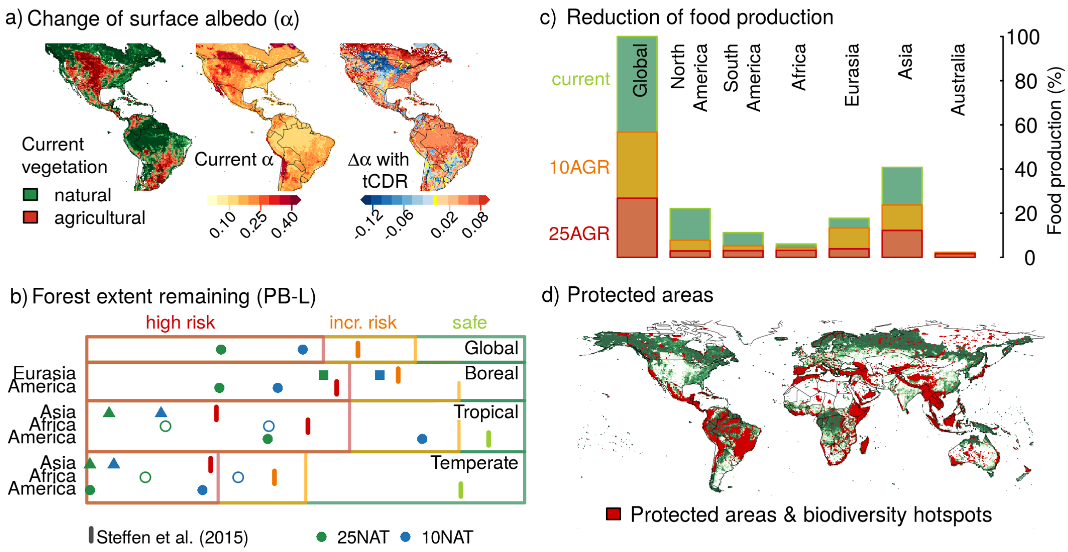

Figure 3.4: The trade-offs of tCDR: (a) Albedo (α) changes caused by tCDR plantations exemplarily for North and South America (only the dominant land type, natural or agricultural, is shown to be replaced by BPs), (b) remaining forest extent (PB-L) in comparison with Steffen et al. (2015) (where symbols represent continents), (c) reduction in food production on cropland, (d) location of protected areas and biodiversity hotspots after IUCN and UNEP-WCMC (2015) and Laurance et al. (2014).

(SI table B.1) due to the replacement of shrubland by BPs, longer growing seasons and higher vegetation densities.

Converting forests to tCDR plantations shifts the status of land-system change (PB-L) from currently being at increasing risk (Steffen et al., 2015) towards being at high risk with a reduction from 62% global forest cover left (current status) to 31–49% in the 10NAT and 25NAT scenarios, respectively (table 3.3; figure 3.4(b)). For example, temperate and tropical forests in Asia found to be most suitable for tCDR would face massive replacements.

Food production would also be affected by tCDR on agricultural land (figure 3.4(c)). Kilocalorie losses would range from 43 to 73% for the 10AGR and 25AGR scenarios, respectively.

In our model, BG and BT biomass plantations on all current agricultural areas would result in 56 kgN ha^{-1}yr^{-1} and 30.79 kgN ha^{-1}yr^{-1}, respectively. According to Karp and Shield (2008) (50 kgN ha^{-1}yr^{-1} for switchgrass, 30-80 kgN ha^{-1}yr^{-1} for willows), Kering et al. (2011) (120–168 kgN ha^{-1}yr^{-1}) and Beringer et al. (2011) (50–70 kgN ha^{-1}yr^{-1}), these values lie at the lower end of former study results. Nitrogen demand for BPs ranges from 169–589 MtN yr^{-1} on natural areas and from 108–200 MtN yr^{-1} on agricultural land. N demand increases over-proportionally: the smaller the selected areas become the more productive they are due to our scenario set up (most productive cells chosen first). For example, 25AGR and 10AGR need much more nitrogen per hectare than the 100AGR scenario. Already the 10AGR scenario demands about three quarters of the current global nitrogen demand of 147 MtN (FAO, 2015) enhancing the pressure on the planetary boundary for biogeochemical flows (44–62 MtN yr^{-1}).

The areas dedicated to tCDR in our scenarios also partly interfere with biodiversity hotspots (Laurance et al., 2014), protected areas (both in figure 3.4(d), IUCN and UNEP-WCMC, 2015) and areas of endangered species (Pimm et al., 2014), which might already be affected by climate change impacts at the levels of warming studied here (Gerten et al., 2013; Ostberg et al., 2013).

3.4 Discussion

3.4.1 The ability of tCDR to delay partially mitigated cumulative emissions

Our simulations demonstrate that the tCDR potential of BPs could be substantial (i.e. up to several decades) if they were implemented immediately at large scale on suitable land as soon as the 1.5°C target is reached around 2038 in a RCP4.5 climate. Our scenarios covering smaller areas could delay the progression on the cumulative emission pathway by almost half a century. If the aim was to balance all cumulative emissions from transgression of the 2.0°C or even 1.5°C target until 2100 on a RCP4.5 trajectory, ca. 330 or 550 GtC would have to be compensated, respectively. While the 2°C target could already be achieved by more restricted (still large-scale) tCDR scenarios, the more ambitious 1.5°C target could only be achieved by the most spatially extensive and far-fetched tCDR scenarios considered here which would imply severe impacts on ecosystems and food production. However, if the INDCs could enforce stronger mitigation results (e.g. if conditional options were fulfilled, air pollution reduced and planned coal fired power plants be cancelled (Edenhofer, 2015; Jeffery et al., 2015), tCDR could possibly reduce the remaining emission gap if the environmental costs incurred were deemed acceptable.

Overall, the areas sizes considered and carbon extraction potential of our scenarios (except for the 100NAT scenario) lie within the range of suggested in previous studies (SI table B.2). Generally, potentials differ due to a broad range of factors such as economic drivers of land allocation, conversion efficiencies, carbon storage options, yield potentials, fertilizers, methodological simplifications or the treatment of the history of the converted land. To our knowledge, only five studies consider tCDR to be a CE method but assume its implementation already in the near future which typically leads to more optimistic outlooks. Caldeira et al. (2013) estimated a carbon extraction rate of 1 GtC yr^{-1} on 3% of the land surface (∼437 Mha) using temperate trees. Our BPs are simulated to be more productive and thus, tCDR on 50% of the 10AGR (523 Mha) could extract ∼2.5 GtC yr^{-1}. The conversion of areas as large as today's agricultural land to tCDR is estimated to yield different potentials (150-900 GtC under mitigated climate in Lenton, 2010, 583–913 GtC in van Minnen et al., 2008, 277–309 GtC in Heck et al., 2016) leaving our result at a medium level (616 GtC), partly due to the simplified utilization pathway of carbon.

3.4.2 The ability of tCDR to balance additional emissions

The potentials of tCDR scenarios would likely still not be sufficient to balance additional emissions associated with a business-as-usual emission pathway like the RCP8.5. Carbon emissions would still increase more strongly than tCDR could compensate despite our carbon sequestration estimates being optimistic due to the preferential selection of most productive grid cells, rapid implementation, beneficial effect of elevated CO_2 on plant growth and the absence of nutrient limitation and biogeochemical feedbacks (e.g. emissions from fertilizers). For example, our model is sensitive to high CO_2 concentrations (Leipprand and Gerten, 2006; Luo et al., 2008; Beringer et al., 2011) acting as fertilizer on plant productivity, and thus, yields may be somewhat overestimated. tCDR potentials would increase by 10–12% on BPs between simulations reaching 390 ppm and our climate forcing of 546 ppm in 2100. An increase of CO_2 concentrations to 1050 ppm as in the RCP8.5 would enhance productivity 17–20% compared to our climate forcing. Natural vegetation is less sensitive to changing CO_2 concentrations with only 4–9%.

3.4.3 The non-economic "costs" of tCDR

We find that the non-economic "costs" resulting from the land conversions for BPs will be high. While it is the purpose of tCDR to possibly go back into the "safe operating space" for climate change (Steffen et al., 2015), it may thus hamper efforts to stay within the planetary boundaries for land-system change, freshwater use (if irrigated), biogeochemical flows and biosphere integrity. A recent study by Wieder et al. (2015) states that the nutrient supply for cultivated land throughout the century is not even secured following the land-use scenarios of the RCPs and thus, neither for our large-scale tCDR scenarios. Our spatially least demanding scenarios (1.0–1.4 Gha) would still restrict food production, reduce forests extents critically and certainly threaten biodiversity. The competition for arable land is already high today (Searchinger et al., 2015) and in view of an increasing world population and its growing demand for food, the obstacles for food production are unlikely to be overcome. Optimistic outlooks on food production and yield increases on currently cultivated land (Lotze-Campen et al., 2010; Alexandratos and Bruinsma, 2012; Powell and Lenton, 2012) suggest that such increases will likely not be higher than 27% globally (Bajželj et al., 2014). According to Ellis et al. (2010) only one fourth of the Earth surface is still pristine and should therefore remain untouched if those areas are to be preserved. Even the conversion of agricultural land to tCDR would not induce a more natural state than today's agriculture (Heck et al., 2016) and the effect of changing albedos cannot be neglected (Arora et al., 2011; Davin et al., 2014; Keller et al., 2014; Miller et al., 2015). Other studies claim that land availability is not constrained (Souza et al., 2015) and that e.g. corridor-like and sustainably managed plantations might also increase biodiversity (Smith et al., 2013b; Jantz et al., 2014; DeLucia, 2015). tCDR would likely increase the already existing and intensifying pressure on managed and natural land.

Our scenarios depict only a small range at the margins of a very diverse space of possible future land-use trajectories, but they still draw ceilings to the achievable potentials and, especially, the bearable non-economic costs for the environment and human well-being. Realistic obstacles for tCDR such as smaller plantation sizes, later and gradual establishment of BPs, climate change impacts on plant growth and water and nutrient limitations would decrease the potential of BPs to sequester atmospheric carbon loading.

3.5 Conclusion

Our study shows that tCDR as a CE method could substantially slow down the progression of cumulative emission on a mitigation trajectory reaching 2.5°C in 2100. However, this can only be achieved if biomass plantations are implemented immediately once the 1.5°C target is crossed and if immense costs for food production and ecosystems were tolerated. Furthermore, it is likely that the extensive conversion of land induces positive feedbacks with the climate system itself (not explicitly modeled here), compromising the purpose of tCDR: to lower the global carbon budget and GMT changes. If tCDR was implemented to counter additional emissions on a RCP8.5 trajectory, this potential would be insufficient despite our rather optimistic sequestration calculations. In view of limited space to reduce side-effects, tCDR can thus be considered as an ineffective CE tool to reverse carbon emissions. We show that we cannot bet on tCDR to supply negative emissions (Fuss et al., 2014; Zickfeld and Herrington, 2015) and that early mitigation, even with sustainably managed tCDR, is inevitable (Smith et al., 2016).

Acknowledgements

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We thank Sibyll Schaphoff for her constant improvements of the model and Julia Pongratz for kindly providing us with data on simulated historical albedo changes.

4 Trade-offs for food production, ecosystems and climate limit the terrestrial carbon dioxide removal potential[1]

[1]This chapter was submitted with modifications as: L. Boysen, W. Lucht, and D. Gerten (2016). "Trade-offs for food production, ecosystems and climate limit the terrestrial carbon dioxide removal potential". *Global Change Biology.*

Abstract

Large-scale biomass plantations (BP) entail trade-offs for food production, ecosystems and climate through land restrictions. The availability of already managed land (i.e. potential abandonment) for the establishment of BP depends on food demand and thus, besides dietary trends, on the interplay of population growth and yield increase. The availability of natural land depends on normative values such as exclusion for reasons of ecosystem or biodiversity protection. The terrestrial carbon dioxide removal (tCDR) potentials of BP in turn depend on the location and productivity of land being considered, management options, albedo changes and biomass conversion efficiencies (CEff). While previous studies identified broad quantitative estimates for trade-offs between tCDR potentials and these diverse land restrictions, we here provide a comprehensive analysis with a wide spectrum of spatially explicit land transformation scenarios, using a global biogeochemical process model. We find, that assumed future needs for nature protection and food production strongly limit tCDR potentials. In none of the analysed scenarios the food demand of a world population growing to 9.5bn in 2050 could be met on current agricultural areas under the assumed future yield increases. Only under a constant world population of 7.5bn people in combination with optimistic outlooks for yield increases (1.4% yr^{-1}) and technology (CEff of 70%), 65 GtC could be sequestered on 380 Mha of released agricultural land between 2050 and 2100. However, if land availability was additionally constrained by adverse albedo changes, this potential would be further reduced by two thirds. Converting instead natural land for BP could result in higher tCDR potentials – but at high environmental costs (e.g. biodiversity loss and ecosystem change).

4.1 Introduction

Terrestrial carbon dioxide removal (tCDR) strategies use the potential of the biosphere to sequester CO_2 out of the atmosphere, which must then be safely and permanently captured by conversion into adequate products (e.g. biochar) to achieve negative emissions. For such purpose, highly managed woody and herbaceous bioenergy plantations (BP) could be cultivated accompanied by regular harvests and subsequent storage of the extracted carbon. BPs are not only a dominant part of the mitigation wedges in many climate projections (Fuss et al., 2014; Klein et al., 2014b; Kriegler et al., 2013) but also part of a climate engineering (CE) portfolio suggested to be possibly put in place in case of failed mitigation. Such tCDR methods intentionally alter the radiative forcing at the top of the atmosphere to reduce global mean temperatures (GMT) by extracting CO_2 out of the atmosphere. Optimistic studies on tCDR rank it as a relatively safe, cheap (Shepherd, 2009) and effective (Klein et al., 2014b; Kriegler et al., 2013; Lenton, 2010) carbon extraction tool. However, substantial uncertainties remain regarding its time- and space-consuming properties linked to high carbon extraction potentials which could ultimately turn tCDR into a rather expensive (Caldeira et al., 2013) and ecologically and socially intolerable (Dornburg et al., 2010; Smith et al., 2013b; Smith et al., 2016) CE method.

A comprehensive biogeochemical analysis of spatial restrictions to BP implementations which prioritize land constraints for food production or nature protection over tCDR potentials is still lacking. This study analyses, spatially explicitly, four factors that may severely restrict large-scale tCDR: (1) food production, (2) ecosystem protection, (3) biogeophysical properties and (4) carbon conversion pathways. Using these constraints enables us to quantitatively explore the global opportunity space of convertible land for tCDR as shown in Fig. 4.1a. Specifically, these components influence the tCDR potential as follows:

1. In order to protect still existing natural ecosystems from further human interference through tCDR, conversion of land is first only considered on already cultivated land. The underlying assumption is that food production per unit of arable land (crops, feed and fodder) could be further increased in the future (e.g. through fertilizer input), and thereby, agricultural land be made available for BP. However, population growth and with it food demand are likely to increase and, hence, make agricultural land expansion necessary (Bajželj et al., 2014; Lotze-Campen et al., 2014; Wise et al., 2009), lowering the land gains from improvements in efficiency and thus, limiting the space available for BP.

2. In a contrasting consideration, natural land might be considered for the establishment of BP to completely safeguard agricultural lands for food supply. The value lands, including terrestrial biomes and protected areas, is difficult to judge since they contribute to ecosystem functioning and resilience, the climate system functioning and human well-being (Chan et al., 2016). Thus, normative decisions would have to be made for the transformation of land (Beringer et al., 2011; Dornburg et al., 2010; Erb et al., 2012; Powell et al., 2013). Both, (1) and (2) could in turn increase carbon emissions due to e.g. management techniques or the effects of land conversions.

3. tCDR plantations are likely to have biogeophysical effects, e.g. if the surface reflectivity (albedo) of the Earth is decreased which might cause local warming

due to increased absorption of sunlight (Arora et al., 2011; Pongratz et al., 2011). Depending on region, case and circumstances these effects could be undesirable and thus, classify these areas as unsuitable for tCDR. For example, a conversion of a bright wheat field into a darker woody biomass plantation could induce a local heating in contrast to the intention of tCDR to lower global mean temperature (GMT). These effects are however highly sensitive to the original land cover and management techniques (see Methods).

4. tCDR land requirements depend furthermore on the conversion efficiency of biomass into different carbon products, i.e. the amount of carbon actually immobilized depends on the emissions incurred along the process chain (Lenton, 2010). For high conversion efficiencies, less land will be needed to gain the same amount of carbon extraction.

Previous studies (Table 4.1) have investigated these dimensions individually or in some form of limited combination. Here we present an analysis that is comprehensive and internally and spatially consistent within one single modelling framework. Kraxner et al. (2013) analysed the possible outcomes of the "Reducing Emissions from Deforestation and Forest Degradation" initiative using an Integrated Assessment Model (IAM) and found that it will likely not be possible to protect all natural areas, halt deforestation, switch to 100% renewable energies and simultaneously feed a growing population. Lenton (2010) describes this circumstance as a trilemma between climate protection, food production and biodiversity conservation. Powell and Lenton (2012) found that only a global shift towards highly efficient food production systems with low meat consumption could release sizable agricultural areas for tCDR (660 Mha). Confirming their previous study, Powell et al. (2013) also emphasized the threat for biodiversity conservation due to biomass withdrawal and habitat loss through bioenergy and food production and climate change. Beringer et al. (2011) focused on two agricultural yield and two ecosystem protection scenarios until 2050 resulting in comparatively smaller areas for BPs with 142-464 Mha on both cultivated and uncultivated land. As they are tied to the net climate effect of BP, albedo changes have to be also accounted for, as topic which has recently gained attention (Davin et al., 2014). All these studies stress the demand for available and suitable land for tCDR, which is regionally limited for food production already today (Licker et al., 2010). A recent work (Smith et al., 2016) takes a first step into the direction of jointly analysing the effects of BPs large enough to reach a 2°C target and the trade-offs for food production, nutrient use, albedo, water and energy and cost requirements using an IAM.

Table 4.1: Results of previous studies dealing with two or more trade-off dimensions investigated in this analysis.

Source	Objectives	Results
Kraxner et al. (2013)	100% renewables, complete stop of deforestation, protection of all natural areas, feed growing population	Not possible; Zero deforestation causes losses of other natural vegetation for managed forests and bioenergy
Lenton (2010)	Trilemma: climate protection, food production and biodiversity conservation	695–1014 Mha abandoned agricultural land for afforestation (68–133 GtC) until 2100. More including natural sinks and residues.
Powell and Lenton (2012)	tCDR potential on agricultural land in dependence on diets and production efficiencies	Expanding agriculture due to high meat consumption and low efficiencies causes loss of natural land.
Powell et al. (2013)	Threat for biodiversity due to food and tCDR production and climate change	Expanding agriculture due to high meat consumption and low efficiencies causes loss of natural land.
Beringer et al. (2011)	Scenarios of agricultural yield and ecosystem protection	142–464 Mha; 28–125 GtC until 2050
Erb et al. (2012)	Bioenergy in dependence to food systems (diets and production), political stability (investments), biodiversity, deforestation, energy crop yields	Biodiversity conservation and political instability could reduce the tCDR potential by almost 50%, while BP yields could increase by up to 50% (compared to outlook scenario 2050)
Smith et al. (2013b)	Reducing greenhouse gas emissions from land while safeguarding biodiversity and food production	Supply side mitigation needs land (sustainable management) less effective than demand side mitigation (improved carbon cascades)
Smith et al. (2016)	BECCS needed to limit warming to 2°C	380–700 Mha extracting 330 GtC
Kato and Yamagata (2014)	Analysis of the required management input of a low emission scenario with BECCS (RCP2.6)	BPs of approximately 440 Mha can only deliver the expected 160 GtC of carbon sequestration under high irrigation and fertilizer inputs.

Here we use a well established biogeochemical process model for natural vegetation and managed land, LPJmL (Bondeau et al., 2007), with a combination of published data sets on biodiversity, to examine the tCDR potentials of BP grown from either 2020 (near-future projections like in most mitigation scenarios) or 2050 (for the purpose of CE) until 2100. These scenarios allow us to systematically assess the tCDR potentials for a suite of different land use scenarios with respect to food demand, ecosystem conservation, albedo changes and conversion efficiencies.

4.2 Methods

4.2.1 The model LPJmL

We conduct spatially explicit simulations with the biogeochemical process model LPJmL for vegetation (including agricultural managed land) and the carbon and water cycle (Bondeau et al., 2007; Schaphoff et al., 2013). All scenarios (described below) depart from the land use patterns including crop and pasture areas of 2005 following Fader et al. (2010) and with irrigation patterns following Jägermeyr et al. (2015). The model is spun up for 5000 years without land use to reach equilibrium in carbon pools and for another 390 years to bring the distribution of potential natural vegetation into an equilibrium. After that, the growth and productivity of dynamic natural and transient prescribed managed vegetation patterns are simulated for the period 1901 to 2005 driven by historical climate data (Ostberg et al., 2015). The agricultural land use patterns and crop shares in each grid cell are held constant thereafter. We chose a climate forcing reaching 2.5°C of mean global warming in the year 2100 (Heinke et al., 2013) and start our tCDR scenarios in 2020 (when +1.1°C is reached) and 2050 (+1.8°C), respectively. The model simulates two types of bioenergy plants, herbaceous and woody (Heck et al., 2016), with global distributions — as constrained by our diverse assumptions (see below) — optimised for best net carbon sequestration. BPs are modelled to be harvested on a regular basis to keep productivity rates high. In this study BPs are assumed to be non-irrigated but to have full nutrient supply. The tCDR potentials given in the analysis always include the net carbon sequestration potential, that is the net outcome of accumulated biomass harvest carbon and changes in land carbon pools (soil, litter and vegetation) due to the establishment and operation of BP. The replacement of natural vegetation is accounted for as a one-time tCDR-harvesting event i.e. carbon emissions from the conversion are reduced accordingly.

4.2.2 Scenario setup

The assumptions for the scenario building process prioritizing food security ("food first", Fig. 4.1a), ecosystem ("ecosystems first") or climate protection ("climate first") are listed in Table 4.2 and described in detail in the following sections. The basic methodology is simple: land grid cells on either agricultural or natural land are sorted according to their productivity (e.g. built-up carbon in crops, pastures or natural vegetation) and protected from conversion to BP along this gradient to the point where the scenario-specific constraints (Table 4.2) are fulfilled. The remaining, less productive grid cells are considered available for the establishment of BP (Fig. 4.1b) without competing against the constraints. We investigate agricultural and natural areas separately but the results are additive. However, as in previous studies (Smeets et al., 2007; Lenton, 2010; van Vuuren et al., 2011b; Powell et al., 2013; Humpenöder et al., 2014) we first concentrate on the conversion of degraded or abandoned crop and pasture land before converting natural land to BP.

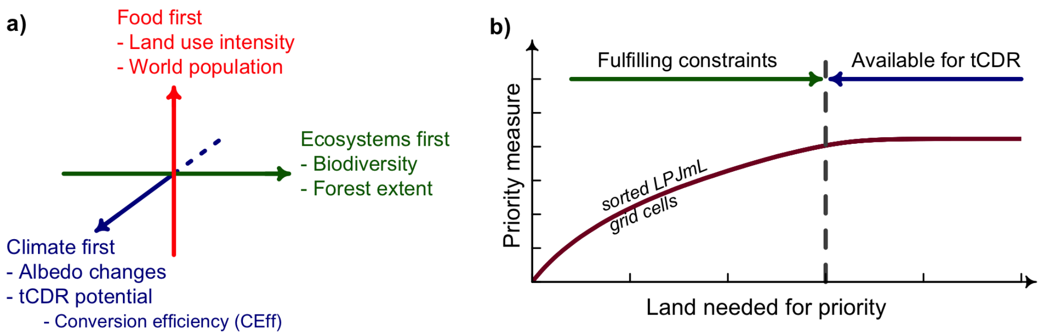

Figure 4.1: Schematic presentation of this study's framework. a) space of opportunities for tCDR framed by the trade-offs between food production, ecosystem conservation and climate protection. b) detection process of land available for tCDR.

4.2.3 Food production

To represent potential future food demand and possible abandonment of agricultural land for tCDR ("food first" scenarios), we apply a range of scenarios of population growth and crop yield increases up to 2050 as documented in the literature (Table 4.2). For reasons of simplicity we assume that these numbers remain constant for the time after BP implementation. Humpenöder et al. (2014) assume a lower-than-current yield increase of 0.48% yr^{-1} for a business-as-usual future pathway until 2100 leading to a total 7.2% increase by 2020 and 21.6% by 2050 (with crop expansions and pasture abandonment). With an alternative assumption of a continuation of the recent (1985-2005) annual increase of productivity for vegetal products by 0.95% (without accounting for the expansion of harvested land; Foley et al., 2011), an increase by 14.3% and 42.8% could be reached in 2020 and 2050, respectively. This increase could even be maintained sustainably if diets shifted towards lower meat shares and highly efficient production schemes (increase by 1% yr^{-1} for all food products, Powell and Lenton, 2012). It is just slightly more than estimates by the FAO outlooks in 2003 and 2006 which stated that increases of 0.9% yr^{-1} are possible until 2050 (Slade et al., 2014). Highest productivity increases in the recent past (1985–2005) reached 1.4% yr^{-1} (including expansion of harvested land; Lotze-Campen et al., 2010; Foley et al., 2011) (amounting to increases by 21% in 2020 and 63% in 2050), which will likely not to be achieved again unless genetic modifications or currently unutilized food plants were entered into use.

Global population numbers refer to 2005's status of 6.5 bn, 2017's likely status of 7.5 bn and a moderate estimate of an increasing population up 7.5 to 7.8 bn in 2020 and up to 9.5 bn in 2050 (United Nations and Affairs, 2015). Yield increases may be seen as opportunities for tCDR if land can be freed where population-driven food demand is outpaced by productivity increases (see Fig. 4.2).

LPJmL's agricultural yield estimates are calibrated with national FAO statistics (Fader et al., 2010) between 1995–2005. Over this period, our model on average produces crop yields of 31 GtC (3300 Kcal cap^{-1} day^{-1} with a population of 6.5 bn in 2005) globally, while pastures produce 18 GtC. Based on this, the maximum leaf area index, one of the crop management parameters in LPJmL, was gradually increased for each crop type and for each country to meet the assumed total yield increases in calorie production in 2020 and 2050, respectively. Climate-driven simulations were carried out with these new management parameters and evaluated while other management parameters (e.g. irrigation) were held constant. We did not allow for agricultural land transitions or expansion since patterns and efficiencies again would induce trade-offs and impacts that are not the focus of this study. Without explicitly distinguishing between vegetal and meat or dairy products and changes in diet we can assume that any yield increase on cropland (linearly) also increases meat production through yield increases on pasture land. Accordingly, we keep the ratio of GtC produced per capita in 2005 on both crop and pasture land constant and take this ratio as a requirement for future food supply.

Table 4.2: Framework and data sets used to identify available land for tCDR.

Food first	Yield increases	Population increases	Land available for tCDR
2020 & 2050	0.48% yr^{-1} (7.2–21.6%) (Humpenöder et al., 2014)	6.5 bn const.	Land not needed to feed the given population
	0.95% yr^{-1} (14.25–42.75%) (Foley et al., 2011)	7.5 bn const.	
	1.4% yr^{-1} (21–63%) (Foley et al., 2011; Lotze-Campen et al., 2010)	7.8 bn (2020) – 9.5 bn (2050, United Nations and Affairs, 2015)	
Ecosystems first	**Protection of**	**Land available for tCDR**	
	Biomes only	Pristine forests (Hansen et al., 2013)	All natural land outside protected areas or/and biomass
		All forests, shrubland, and grass land	
	Protected areas	Biodiversity hotspots + protected areas + endangered species + endemism richness (Kier et al., 2009).	
	Biomes + protected areas	all forests and biodiversity areas	Unproductive/ unprotected lands
Climate first	Albedo effects	Protection of pixels with albedo changes exceeding -0.02 after the conversion to BP.	
	Conversion efficiencies (CEff, %)	Low: 20% Medium: 50% High: 70%	

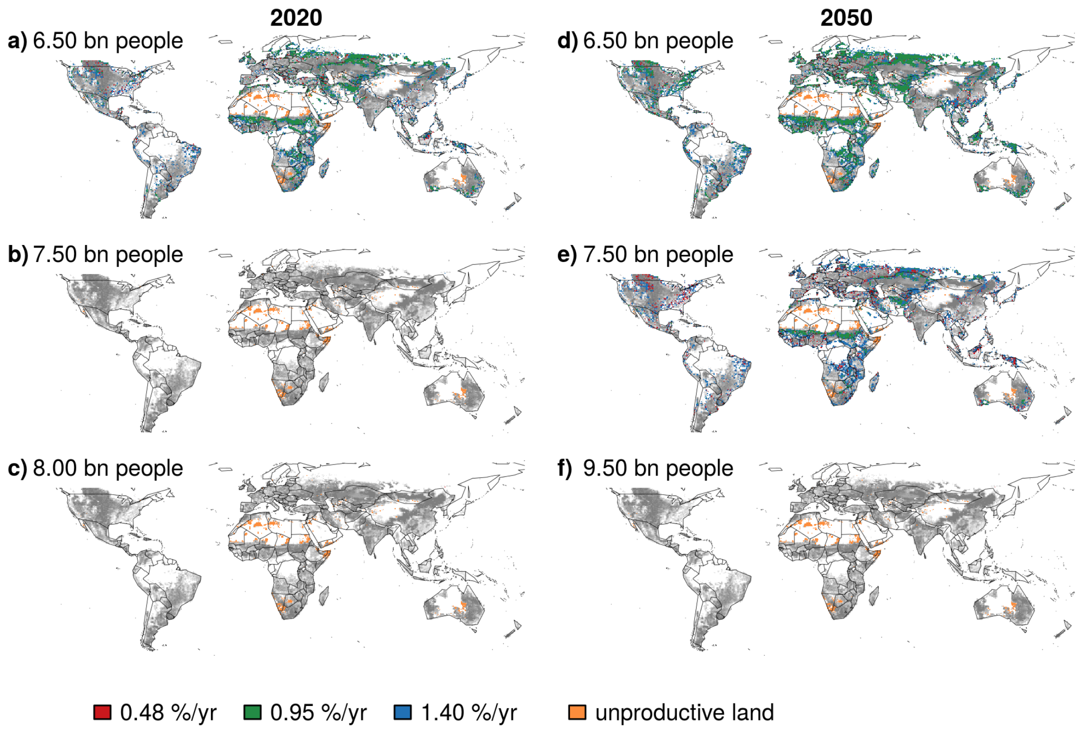

Figure 4.2: Available land for tCDR (coloured) on agricultural areas (grey) according to the scenario-specific constraints assuming tCDR implementation starting in 2020 (left) and 2050 (right), respectively.

4.2.4 Degraded and unproductive soils

Some of agricultural land is rather unproductive and contributes little to food, fibre or cotton production and would therefore be available for BP. We identify these areas by taking the 90^{th} percentile of least productive agricultural land grid cells, which are mainly located at the margins of deserts or mountainous regions. The assumption is that under appropriate management of BP, these areas could potentially be productive for BP. Similarly, BP could be used to restore degraded land (Qin et al., 2011; Xie et al., 2013). We additionally use the Global Assessment of Human-Induced Soil Degradation (GLASOD, Supplementary Information, SI Fig. C1; Oldemann et al., 1991) data set to identify this degraded land. Contrarily to the unproductive agricultural land grid cells identified by LPJmL, degraded soils are not simulated explicitly in the model. Therefore, we assume the case that soils could be fully restored by 2020 or 2050 and deduce optimistic potentials for (non-irrigated) BP on these areas.

4.2.5 Natural and protected areas

To avoid conflicts with food production, natural land might be considered alternatively for the conversion to BP. However, the value of these areas is difficult to measure quantitatively but they play an important role in the climate system and biodiversity supports resilience. In this section we therefore classify biomes and overlay biodiversity maps to systematically test the tCDR suitability and potentials of these areas ("ecosystems first" scenarios).

Natural biomes are classified from model simulations with constant land-use patterns until 2020 or 2050 using climatic conditions and carbon contents (Ostberg et al., 2013). For the analysis we here distinguish between forested areas, grass and shrubland. Hansen et al. (2013) identified pristine forest areas as intact forest landscapes which are therefore part of the forest biomes considered here (Fig. 4.3a).

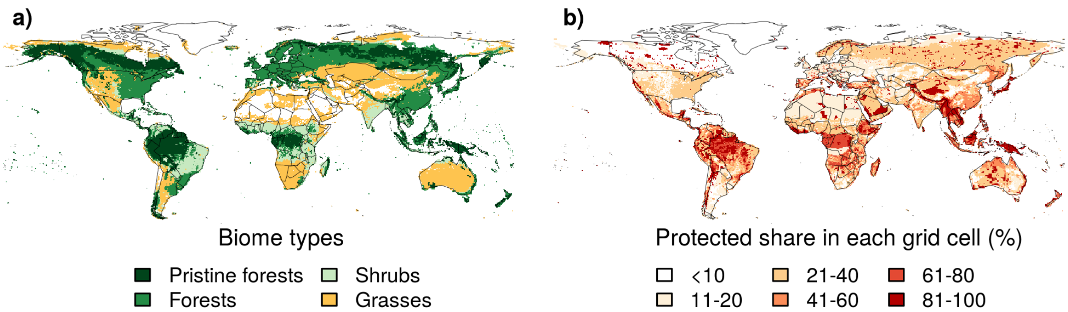

Figure 4.3: Maps displaying the distribution of major biomes in 2020 (a) and grid cell fractions of protected areas (b) considered for protection or the establishment of BP in this study.

We further overlay maps of biodiversity hotspots (Laurance et al., 2014), endangered species (Pimm et al., 2014) and endemism richness (Kier et al., 2009) (Fig. 4.3b). While hotspots cover entire grid cells, areas of endangered species and endemism richness are normalised by their maximum values and translated to fractional shares of grid cells and the dominant one of both data sets is taken. If BP and protected areas appear together in one grid cell, it is assumed that BPs always interfere with the protected areas although these could be located anywhere in the cell. Due to this procedure, in case of conflict precedence is given to BP, we maximise the projected potential to the detriment of protected area.

Biome classes and biodiversity maps are either protected separately (e.g. only forests, shrubland or protected areas) or in combination (e.g. forest and shrubland) while the other classes of natural land are available for tCDR. However, grid cells are excluded in which non-irrigated BP saplings do not grow due to climatic conditions.

4.2.6 Albedo changes

LPJmL calculates surface albedo depending on area covered by vegetation and snow cover in each grid cell (SI Fig. C2a; Forkel et al., 2014; Strengers et al., 2010. Studies showed that the conversion of grassland to BP in higher latitudes might shadow bright snow, causing a warming effect (Schaeffer et al., 2006; Arora et al., 2011). In this study, albedo values for BP have been set to 0.18 for bioenergy grasses (Caiazzo et al., 2014) and 0.16 for bioenergy trees (Schaeffer et al., 2006). Residue management after harvest management is an influential factor regarding surface albedo. In LPJmL, these are assigned a value of 0.32 for straw (Kucharik et al., 2013) and 0.27 for crop stubble (mean of Merlin et al., 2013; Davin et al., 2014; Horton et al., 2015) of bioenergy grasses. Straw and stubble from both, crops and BP are left on the field to decay and thus, partly reduce the impact of the soil albedo. Based on our settings, albedo decreases on much of the agricultural land if converted to BP (SI Fig. C2b). In comparison with historical albedo changes due to land use change (Pongratz et al., 2011), our simulated changes are rather at the high end. We only include changes that exceed -0.02 of the original albedo value to account only for pronounced alterations of the surface reflectivity ("climate first" scenarios). On natural land albedo exclusively increases after a conversion to BP which is why these effects are not included in the analysis on tCDR potentials on these areas (SI Fig. C3).

4.2.7 Conversion efficiency

We here span the range of possible conversion efficiencies (CEff), including all losses, from a pessimistic 20% to a medium level of 50% to improvements up to 70%. In the following, all tCDR potentials refer to values of CEff of 50% unless stated differently.

Harvested biomass from BP contains carbon that needs to be further processed to be climatically beneficial: i.e. carbon needs to be extracted from the carbon cycle to achieve negative emissions. Methods include the substitution of fossil fuels by transforming biomass into biofuels in combination with carbon capture and storage (BECCS) to geological reservoirs; the increased traditional use of wood as a building material or the production of biochar which is brought back onto fields and might act as a fertilizer and reduce the use of nitrogen and phosphorus. The ultimate carbon extraction depends not only on the decay time of the end product but also on the losses and leakage rates during harvest, transportation and, especially, conversion techniques and feedstocks used (Edenhofer et al., 2011). Wood combustion without (20–40%) and with added coal (30–40%) as well as fermentation of lignocellulosic grasses (33–35%; Lenton, 2010; Edenhofer et al., 2011) are certainly at the lower end. Gasification methods reach between 50–90% (Lenton, 2010; Edenhofer et al., 2011) depending on the by-products and techniques used and whether heat or fuel should be the result. Pyrolysis for the production of biochar has an estimated efficiency of 50–85% (Lenton, 2010; Woolf et al., 2010). However, losses during production, transport and storage of 2–15% (Cannell, 2003; Smeets et al., 2007) need to be accounted for. Long-term storage capacity estimations vary between 600 GtC (Azar et al., 2010), 1080 GtC (Humpenöder et al., 2014), 460–3030 GtC (Vaughan and Lenton, 2011) and 3000 GtC (Lenton, 2010) for carbon capture and storage (CCS). Biochar, though assumed to have lifetimes of up to millennia (Woolf et al., 2010), can only be distributed on fields as long as the carbon uptake limit of 400-500 GtC is not reached before possible negative effects occur (Lenton, 2010). However, biochar is assumed to have positive effects on the fertility of soils and may therefore reduce artificial fertilizer input. Wood burial could theoretical have an efficiency of 100%, if wood is stored under anaerobic conditions, the practical realization is, however, unrealistic in most respects (Zeng, 2008).

4.3 Results and discussion

4.3.1 Conversion of agricultural land

The conversion of agricultural land to tCDR plantations is strongly restricted by food demand which in turn depends on population growth and land use intensity in particular ("food first"). Simulated global food production (Fig. 4.4) levels off when reaching an area as large as 3 Gha, which means that these areas are not adding substantially to the food production. Transforming the 10% least productive agricultural land grid cells (86 Mha, Fig. 4.2, Table 4.3) to BP reveals that these areas are also unsuitable for the cultivation of non-irrigated BP, with only 1 GtC sequestered. Some studies claim that BP could restore marginal soils (McElroy and Dawson, 1986; Xie et al., 2013) but others hold against that carbon emissions from land conversion and BP operation are high (Qin et al., 2011; Qin et al., 2014). Searchinger et al. (2015) also point out that the definition of what degraded lands are, and how they could be used, is highly uncertain (e.g. they could nonetheless provide valuable natural habitats). LPJmL simulates sizable biomass production potential on currently degraded soils (SI Fig. C1) such that if severely and extremely degraded soils covering about 300 Mha were restored until 2020 or 2050, 67 and 44 GtC could be extracted, respectively (Table 4.1). If all slightly and moderately degraded land was converted to BP, 203 to 300 GtC could be extracted on 1654 Mha – although it might still be partly used for agriculture today.

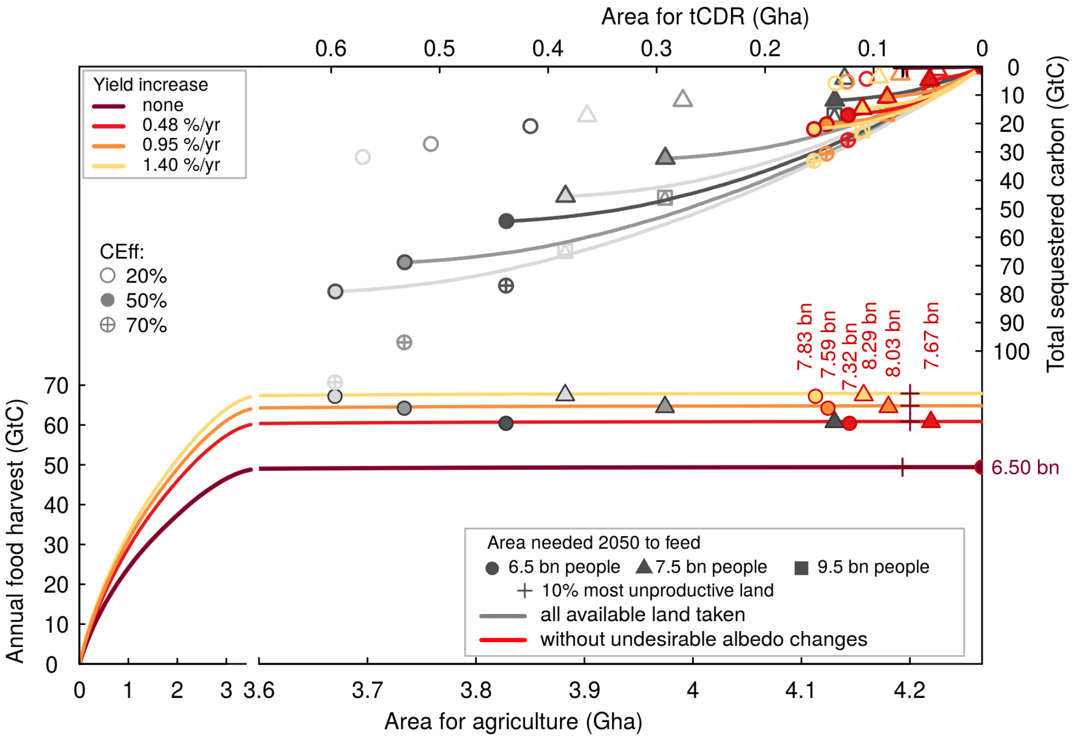

Figure 4.4: Relation between agricultural harvest, world population, and land that could be released for tCDR — with and without accounting for albedo effects. If agricultural yield increases (lower axes, coloured lines) satisfy the food demand of a given population (grey symbols on lower lines) until 2050 land could be released for tCDR. BPs could be established on this available land (corresponding upper axes, grey lines) to deliver tCDR potentials (GtC) between 2050–2100. If negative albedo changes exceeding -0.02 constrain additionally the land availability, a higher population could be fed (colored symbols on lower lines) while tCDR potentials decrease simultaneously (upper axes, coloured lines). Different levels of tCDR conversion efficiencies (CEff) are also represented. (For a tCDR runtime period of 2020–2100 see SI Fig. C4)

Table 4.3: Available land area under various assumptions about world population growth and yield increase until 2020 and 2050 and the resulting tCDR potential (GtC) on this land in dependence on the conversion efficiency (CEff). Excluding areas with unfavorable albedo changes after the conversion to BP reduces the tCDR potential but increases the amount of people to feed. Additionally, the area saving resulting from an increase in CEff from 50% to 70% is given.

Year	Scenario	World population (bn)	Area for tCDR (Mha)	tCDR potential (GtC) in dependence of CEff			Area saving due to CEff increase from 50% to 70% (%)
				20%	**50%**	**70%**	
2020	Unproductive land		73	0	1	1	
	0.48% yr^{-1}	6.50	279	16	45	64	-58
	With albedo	6.91	83	4	16	24	-65
	0.95% yr^{-1}	6.50	335	21	57	82	-56
	With albedo	7.03	101	5	20	30	-64
	1.40% yr^{-1}	6.50	383	25	68	96	-56
	With albedo	7.14	113	6	24	36	-63
2050	Unproductive land		73	0	1	1	
	0.48% yr^{-1}	6.50	438	21	54	77	-53
		7.50	136	4	12	17	-58
	With albedo	7.32	123	4	17	26	-62
		7.67	48	1	5	7	-62
	0.95% yr^{-1}	6.50	532	27	69	97	-52
		7.50	292	12	32	46	-56
	With albedo	7.59	143	5	20	31	-61
		8.03	87	3	11	17	-63
	1.40% yr^{-1}	6.50	571	32	79	111	-51
		7.50	384	17	46	65	-54
	With albedo	7.83	155	6	22	33	-60
		8.29	110	4	15	22	-62

Agricultural land can only be freed for BP if yield increases until 2020 or 2050 (Fig. 4.4, lower axes) will exceed the concurrent food demand for a given world population (Fig. 4.4, grey symbols on lower lines). Total yield increases considered here by 2050 (21.6, 42.8 and 63%) are sufficient to produce food for up to 7.5 bn people while still releasing 136, 292 and 384 Mha land for BP (Fig. 4.4, upper axes, grey lines) with tCDR potentials of 12, 32 and 46 GtC, respectively. However, in none of these scenarios land could be released for tCDR if food was to be produced (without cropland expansion) for population numbers up to 9.5 bn, which is rather likely (Bajželj et al., 2014; Sakschewski et al., 2014). BP established in 2020 are simulated to be in place for 80 years but total yield increases are still too small to provide for a world population of 7.5 bn and thus, land for tCDR would only be available under lower population numbers in 2020 (SI Fig. C4). Of course, regional differentiations of yield increases and the possibility of trade could possibly also lead to land abandonment in certain regions that exceeds the extents considered in this study. Linked to this, a shift towards a low-meat diet could free additional pasture land which is a scenario also under debate (Erb et al., 2016; Powell and Lenton, 2012). Overall, the prospect of sustainably increasing global food production while protecting the environment poses challenges already today (Hertel and Baldos, 2016) – demonstrating the difficulty of freeing land for BP in the future if expansion is undesirable and yield increases are only moderate.

If we restrict the available land from a biogeophysical point of view, i.e. take out areas where albedo effects of land conversion to BP plantations would lead to a warming ("climate first"), land availability will be reduced substantially (Table 4.3). Proportionally to the areal reduction (upper axes, coloured lines), tCDR potentials from BP are reduced by 60 to 70%. Yet, this spared land is still available for food production and sufficient to feed, depending on the yield increase, up to 7.14 bn people for the 2020 BP onset time at 6.5 bn people (SI Fig. C4) and 7.67–8.29 bn people departing from 7.5 bn in the 2050 onset scenario (Fig. 4.4, coloured symbols on lower lines). Some studies support exclusion of such biogeophysically unsuited areas (Schaeffer et al., 2006; Singarayer et al., 2009; Arora et al., 2011). Other, recent studies hold against, that bioenergy grasses, in contrast to conventional cropland, experience longer growing seasons and several harvest events a year, leading to a coverage of the dark agricultural soil. This in turn could make them an effective mitigation tool due to surface albedo increases (Merlin et al., 2013; Davin et al., 2014) and thus, the tCDR potentials without albedo restrictions would apply. A more detailed analysis with a coupled biosphere-atmosphere model would be needed to further analyse whether changes from the extraction of CO_2 by tCDR overcompensate changes in albedo (through changes radiative forcing, Pongratz et al., 2011) or whether changes in moisture fluxes play a role.

Technical improvement of conversion and storage efficiencies could increase the net carbon extraction and reduce the area needed for the effective sequestration of one unit of carbon. For CEff of 20%, carbon losses due to the conversion of land cover to BP cannot be fully offset and thus, the suitable area for BP is reduced compared to higher values of CEff (Fig. 4.4). Figure 4.5 concentrates on the BP area saving of increasing CEff from 20% to 50% or 70% while keeping the tCDR potential of a specific scenario constant. The area saving, for example if CEff increases from 50% to 70% (Table 4.3), is immense with reductions of 51–65% of the convertible agricultural land. This means that the same amount of carbon could be extracted out of the atmosphere on about 40% of the most productive available land cells if carbon losses during transportation, processing and storage are decreased by at least 30%. Some studies argue that high rates of permanent sequestration are possible, for example by concentrating on biochar or CCS (Lenton, 2010). However, it is uncertain that the highly efficient techniques could be applied uniformly and at large scales due to limitations in storage capacity (e.g. of soils or geological reservoirs) or additional non-BP feedstock demand (Fuss et al., 2014; Kato and Yamagata, 2014; Smith et al., 2016).

Overall, albeit relatively low, the simulated tCDR potentials studied here are rather optimistic since our scenarios rely on very productive BP characterized by, for example, unlimited nutrient supply and fast implementation. Especially the beneficial effects of a moderately warmer climate and elevated CO_2 levels increase plant productivity in the second half of the century in our model by 12–15% (on BPs in simulations with 546 ppm compared to 390 ppm) whereas many studies reduce CO_2 concentrations more strongly than in our setting due to simultaneous mitigation efforts (Lenton, 2010) or they limit their study period to 2050 (Beringer et al., 2011; Powell and Lenton, 2012). Contrarily, the absolute potentials found here are lower than other results (Table 4.1), which is due to our application of rather strict land protection without the possibility of crop and pasture land expansion into natural land as is allowed for example in many IAM-based studies (van Vuuren et al., 2011b; Popp et al., 2014a). Such land cover transitions would again interfere with ecosystems (e.g. through deforestation, Humpenöder et al., 2014) with trade-offs similar to those of BP, as described in the next section.

4.3.2 Conversion of natural land

Analogous to the above analysis for abandoned agricultural land, we map the different tCDR potentials following various degrees of ecosystem protection (“ecosystems first”).

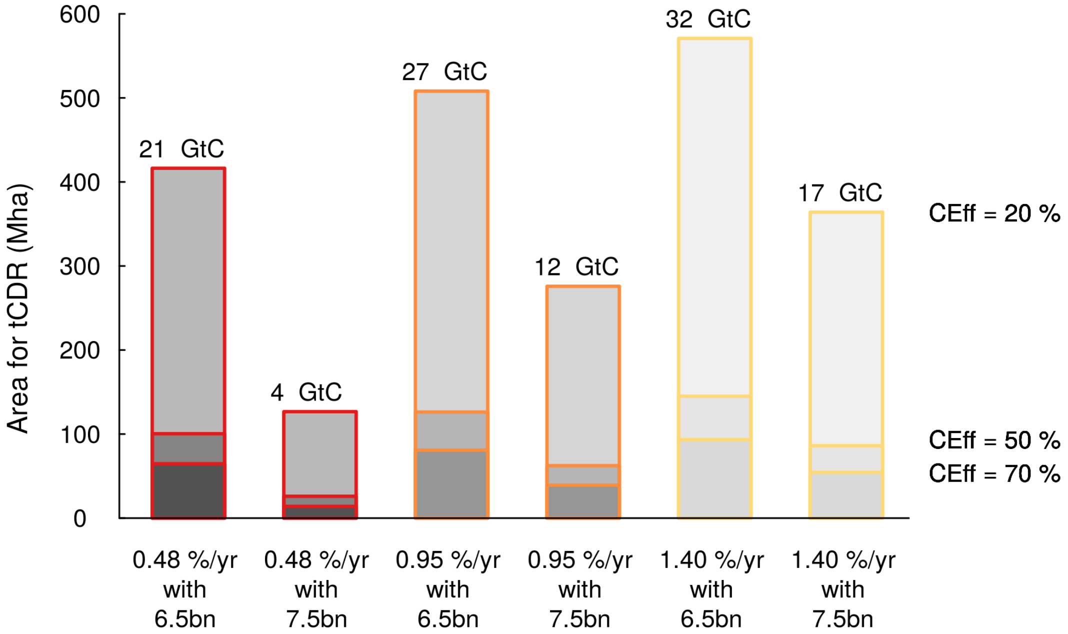

Figure 4.5: Comparison of the land requirements to permanently extract the same amount of carbon with CEff of 70% or 50% compared to 20% for the time period 2050–2100.

Figure 6 shows the simulated vegetation carbon for different combinations of protected biomes and biodiversity maps (lower x-axis) against the tCDR potential on the released areas (upper x-axis) for the period 2050–2100 (SI Fig. C5 shows the results for 2020–2100). Total biomass carbon levels off, that is it does not increase further on areas greater than forest and shrubland combined (ca. 6 Gha, SI Table C.2). Although this land could be rated as unproductive, 11–12% of protected areas would be lost (additional 1.7 Gha) for a comparatively small sequestration potential of 87 GtC and 56 GtC in 2020 and 2050, respectively. Note that available land for tCDR declines with proceeding climate change in our model since forests expand in response to climatic change by 264 Mha by 2050, especially at high latitudes. The unproductive land covers mainly barren land such as deserts (or tundra) and intense management of BP like irrigation would be necessary to improve BP yields there.

Converting large areas for the purpose of tCDR could strongly increase the sequestration potential compared to the restrictions applied to agricultural land – though at the costs of terrestrial ecosystems. Assuming that protecting areas smaller than at least 50% of the natural land (e.g. pristine forests, grass land or shrubland) is likely unrealistic, we focus thus on scenarios that, in combination or alone, exclude areas larger than

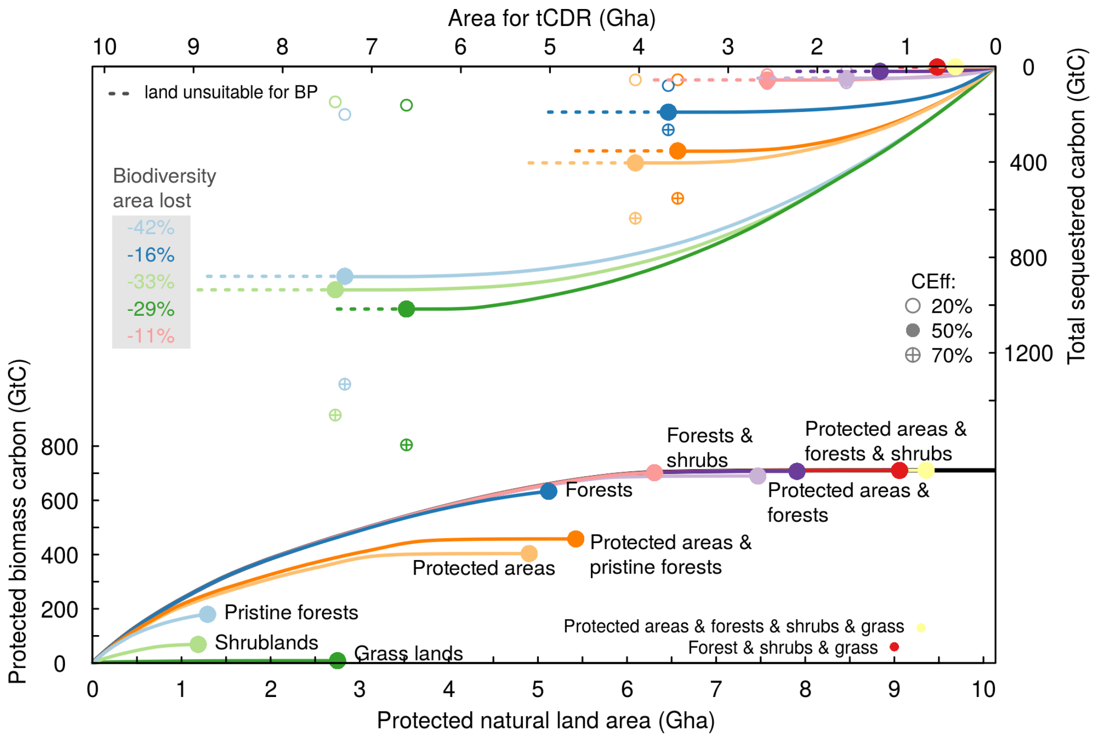

Figure 4.6: Relation between different degrees of ecosystem protection (see Fig. 4.3) and the corresponding tCDR potential on the released land (similar to Fig. 4.4). Vegetation carbon (GtC) of conserved areas (lower axes) and the tCDR potential (GtC) of BP on unprotected areas (upper axis) depending on different levels of conversion efficiencies (CEff) for the period 2050–2100 (upper axes). (For the period of 2020–2100 see SI Fig. C5).

this. For example, the preservation of all protected and forested areas would yield a tCDR potential of 565 GtC (on 3.5 Gha) starting in 2020 and 354 GtC (on 3.6 Gha) starting in 2050 (Table 4.3). These potentials per unit of area converted are much smaller than those achieved on agricultural land since higher land conversion emissions counteract substantial parts of the sequestration potentials. Stronger land protection (all scenarios protecting larger areas than forests and shrublands) leads to small tCDR potentials with at maximum of 3-32 GtC on (0.7–1.3 Gha) established in 2020.

Considering that the rate of biodiversity loss is already exponentially increasing (Ceballos et al., 2015) and that ecosystems will likely be exposed to climate change impacts during the next decades (Gerten et al., 2013; Ostberg et al., 2013), rededicating more natural land to BP is a delicate task. There are however studies arguing that corridor-like BP or afforestation projects could favour biodiversity, protect ecosystems and even favour the potential of BP (Jantz et al., 2014). Still, sacrificing natural areas which are rich in carbon storage, biodiversity and needed for ecosystem resilience would request delicate decision-making and the added value of tCDR for climate protection against the multi-faceted value of original land cover would still have to be proven.

We conclude that the land availability for tCDR is very limited if constrained by the simultaneous needs for food production as well as ecosystem and local climate protection through albedo changes. Our scenarios cover a range of yield increases considered in literature, but only the highest yield increases in combination with a stagnating or declining world population could free agricultural land for tCDR by 2020 or 2050. These available land areas would again be reduced when accounting for undesirable albedo changes leading to local warming effects. Only changes in dietary trends or new, less space-demanding food sources could release additional land. Although the possibly available natural areas cover large areas reported here, land conversion emissions have first to be overcome and the ecological costs such as the loss of biodiversity or pristine forests are considered to be high. Greatest potential to approach a satisfaction of all constraints with still substantial tCDR potentials could lie in the improvement of highly efficient carbon utilization pathways which reduce the carbon losses along the process chain. Rapid mitigation, with only small contributions of BP on selected areas like degraded land, thus appears to be inevitable.

Acknowledgements

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5 The bioenergy potentials and trade-offs in the scenario world of RCP2.6

The results presented in this study are preliminary and were conducted under the supervision of Prof. Timothy Lenton during a research stay at Exeter University in April 2016.

5.1 Motivation

After having created and analysed scenarios of BPs following different priorities (Chapters 2–4), RCP2.6 provides a peer reviewed, published and commonly used scenario for land-use including BPs (van Vuuren et al., 2011b). Out of the four RCPs, RCP2.6 achieves the lowest radiative forcing by 2100 due to the employment of negative emission technologies like the use of bioenergy in combination with carbon capture and storage (BECCS). By the end of the 21st century emission reductions, the increase of nuclear power and BECCS result in net negative emissions of 1 GtC yr^{-1} limiting the GMT increase to below 2°C.

RCP2.6 was developed by the working group around the Integrated Model to Assess the Global Environment (IMAGE) between 2007 and 2011 (van Vuuren et al., 2007; van Vuuren et al., 2010; van Vuuren et al., 2011b). In 2011, it finally entered the CMIP5 framework (Taylor et al., 2009) and constituted a major part in the analyses presented in IPCC AR5 (Stocker, 2013). At that point of time, participating coupled climate models began, for the first time, to include land surface processes and thus, represent closed carbon cycles. However, most models could only represent one crop and pasture type and were not able to simulate specific agricultural land types such as bioenergy crops. Most CMIP5 simulations were driven by provided CO_2 concentrations and therefore did not require the assessment of tCDR potentials through the establishment of BP (i.e. their ability to lower CO_2 concentrations).

By now, the research community has become curious about the feasibility of tCDR as described in Section 1.4. With LPJmL we are now able to analyse the land-use patterns provided by the IMAGE group using climate forcings provided in turn by coupled climate models that participated in CMIP5. A recent publication already indicates that high management inputs and productive bioenergy plants are necessary to meet the required BECCS level demanded by RCP2.6 (Kato and Yamagata, 2014). Here, I will compare tCDR potentials calculated by LPJmL to those defined by van Vuuren et al. (2011b) and reproduced by Kato and Yamagata (2014) and further investigate the proposed development of food production.

5.2 Materials and methods

RCP2.6 is a peak-and-decline scenario meaning that emissions peak around 2050 at 490 ppm before declining to 420 ppm in 2100. Land-use data projections follow up on the historic data sets of the HYDE data base and were harmonised for a smooth transition towards 2005 (Hurtt et al., 2011). Compared to the land use data set underlying the previous studies of this thesis, differences arise mainly due to the definition and identification of grass lands (see Fig. 5.1). The global population is assumed to grow up to 9 billion (bn) people in 2050 while consuming more meat than today. Increasing land-use intensity allows for agriculture to concentrate in poorer world regions while the abandoned land in wealthier regions can be used for the establishment of BPs (see Fig. 5.2a.). BPs are only allowed on abandoned crop and pasture land or natural, non-forested and non-protected land. This in turn causes deforestation to meet the increasing food and energy demand and to compensate for a decreasing CO_2 fertilization effect. Land-use change is therefore only demand driven and not by climate policies.

The creation of annual land-use data sets for LPJmL following the RCP2.6 specifications held some difficulties and assumptions were necessary.

The RCP data base (`http://luh.umd.edu/data.shtml`) provides annual data for crop and pasture shares in each grid cell on a 0.5° x 0.5° grid. While those two agricultural land types have been harmonised (fitted to historic land-use data), fractions of bioenergy were added at a later point and not fitted to the existing data. According to the data documentation, bioenergy shares are part of the crop land shares. However, in many cases bioenergy shares exceed not only those of crop land, but also of total agricultural land (crop plus pasture land), and expand into natural land. The reason is that in the majority of cases bioenergy fractions cover between 90–100% of the entire grid cell leaving no room for other land-uses. In total, 440 Mha of land are covered with bioenergy in 2100 (see Fig. 5.2b.).

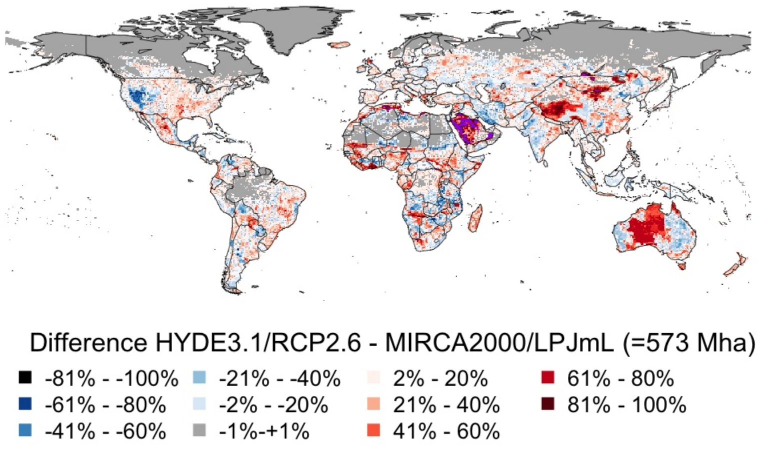

Figure 5.1: Map showing the difference between the historic RCP data set (based on HYDE3.1) and the LPJmL base data set (based on MIRCA) in 2005.

LPJmL simulates 12 different crop types, plus one class covering all nutritious, fibre and other plants and another class for pastures (Fader et al., 2010) all with irrigated shares as described by Jägermeyr et al. (2015). The RCP land-use patterns only provide one single crop type. Therefore, the land-use data set used in LPJmL for the previous studies is used as a basis for crop mixes and irrigation shares (see also SI D.1). For the historical period, annual crop mixes are transferred proportionally to meet the required RCP total crop shares. From 2005 on, the last year of the base data set, crop mixes are held constant. In cases of grid cells that do not contain crop or pasture land in the base data set but do so in the RCP data, the national mean crop mix was applied. The expansion of crop land could either happen partially irrigated (e.g. proportionally to 2005's state) or non-irrigated. Similarly, bioenergy can also be partially irrigated (e.g. the sum of irrigated crops and bioenergy meets the proportional increase of 2005's state), fully irrigated (no water limitation) or non-irrigated. As before, plants in LPJmL are fully supplied with nutrients which would refer to a high fertilizer application.

According to the publications on RCP2.6 (van Vuuren et al., 2007; van Vuuren et al., 2009; van Vuuren et al., 2010; van Vuuren et al., 2011b), bioenergy is supposed to provide 118 EJ (exajoules) by 2050 and 225 EJ of energy by 2100. Cumulative bioenergy should produce 11.7 ZJ (zettajoules) between 2000 and 2100 with 7.0 ZJ (equal to 7,000 EJ) coming from woody bioenergy and 4.7 ZJ coming from residues. Woody energy is thereby defined as any secondary bioenergy plantation ("e.g. willows or switchgrass", van Vuuren et al., 2010). Assuming that one kilogram of dry mass contains and energy

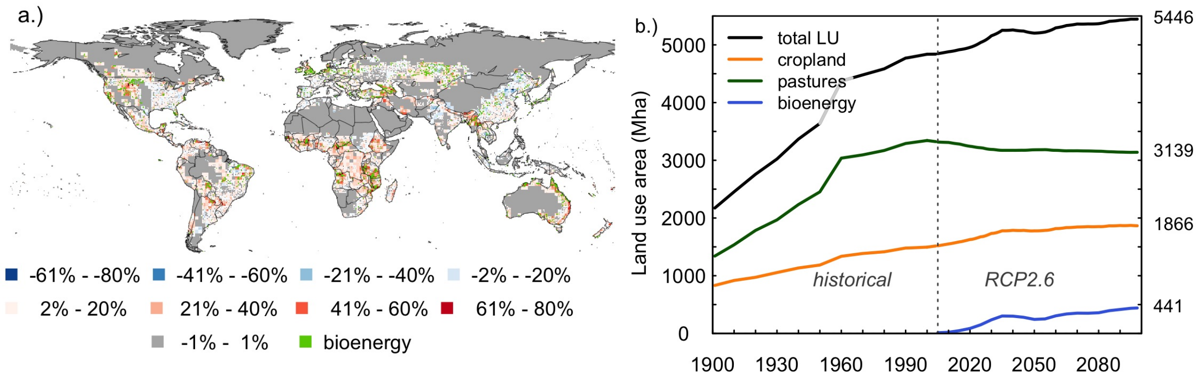

Figure 5.2: a.) Map showing the changes in land-use from 2005 2099; b.) Evolution of crop, pasture and bioenergy area in RCP2.6 from 1900 to 2099.

content of 18.5 mega joules, 189 GtC should be sequestered out of the atmosphere by BPs. In contrast, (Kato and Yamagata, 2014) yield an extraction potential of 160.9 GtC, claiming that this represents 101.3% of the BECCS requirements in this scenario (amounting to 159 GtC). By the end of the century the carbon flux should amount to 3 GtC yr^{-1} from BECCS. For simplicity and due to higher biomass harvest potentials than for bioenergy trees (BT, Heck et al., 2016), only bioenergy grasses (BG) are shown and analysed in this chapter.

Five CMIP5 models provided climate data that was already evaluated in Brovkin et al. (2013) and Boysen et al. (2014). The models used here are HadGEM2-ES (Had), MPI-ESM-MR (MPI), CanESM2 (Can), IPSL-CM5A-MR (IPSL) and MIROC-MR-CHEM (MIR). Their simulated climate outputs were biased-corrected following Watanabe et al. (2012) and Heinke et al. (2013) but for continuous time series and used as climate input for LPJmL. As shown by Brovkin et al. (2013), the resulting GMTs in 2100 differ among the models: while Had, Can and MIR lie approximately 1.7°C above 2005's GMT of 14°C, IPSL and MPI only increase by approximately 1.1°C and 0.7°C, respectively. Atmospheric CO_2 concentrations are the same for all models and prescribed to LPJmL according to RCP2.6.

Conversion efficiencies (CEff) from biomass harvest potentials on field to the finally long-term captured carbon base on the evaluation in Chapter 4. However, here a more optimistic approximation is made with CEff levels of 50, 75 and 90%.

5.3 Preliminary results and discussion

As stated before, these results are preliminary and analyses not completed. However, these first figures and numbers already hint towards significant new findings regarding RCP2.6.

5.3.1 Land carbon development

The first result is the response of the simulated carbon cycle in LPJmL to the different climate forcings (Fig. 5.3 a.). Not only may precipitation patterns differ, but the GMT increases also vary. Since CO_2 concentrations are always identical, the changes in land carbon (soil, litter and vegetation) are due to these precipitation and temperature effects, e.g. due to an overcompensating increase of heterotrophic respiration over CO_2 fertilization. Therefore, land carbon decreases constantly in response to the climate inputs of Had (1.7°C), Can (1.6°C) and MIR (1.9°C) with -70 GtC, -77GtC and -86 GtC, respectively. In MPI and IPSL,land carbon first increases before declining from mid-century on reaching -31 GtC and -23 GtC, respectively. Without the land transformation to BPs, land-use change emissions would be about 20 GtC smaller for each climate forcing. This is mainly caused by the transformation of natural areas to managed bioenergy land if crop and pasture land were exceeded.

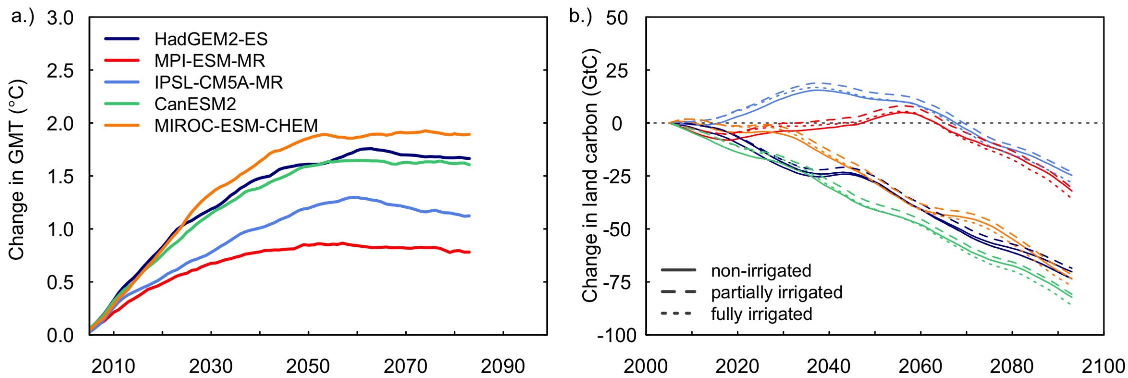

Figure 5.3: a.) Development of GMT as simulated by the different climate models; b.) development of land carbon in LPJmL resulting from different climate model input data sets and irrigation management.

The response of land carbon dynamics in LPJmL deviates from those found by Brovkin et al., 2013 for different reasons. In this previous study only Can and MIR showed negative land carbon changes (-10 and -25 GtC) while all other models simulated a relatively strong increase of land carbon of 150 to 200 GtC. In these models, land-use was implemented according to model specific schemes and not as detailed as done in LPJmL. Also, simulations were conducted on a much larger grid due to computational and temporal costs. Although CO_2 concentrations are identical, land-atmosphere feedbacks could still occur and thus, precipitation and dynamic natural vegetation patterns might have favoured each other. In LPJmL, the distribution of natural vegetation can only react, but not feed back, to the given atmospherical inputs which might indeed represent unfavourable growing conditions. Further, the CO_2 fertilization effect was not overcompensated by the increase of heterotrophic respiration caused by the increase in GMT. Based on evaluations of LPJmL for the historic period, we can still approve the model's calculation with a given caution on the structural model differences.

5.3.2 Bioenergy harvest potentials

Fig. 5.4 shows the development of cumulative annual biomass harvest fluxes. If all carbon could be permanently stored (CEff = 100%), rainfed BG plantations could just fulfil the lower RCP2.6 goal of extracting 160 GtC by 2100 with a model spread of 152–159 GtC. With partial and unlimited irrigation this potential could increase up to 326–339 GtC and 450–459 GtC, respectively. However, carbon losses lead to 10–50% lower conversion efficiencies. Kato and Yamagata (2014) compared annual BECCS potentials of different bioenergy crops and management options against the requirements of RCP2.6. In their study, only second generation bioenergy plants (e.g. BG and BT) under high management input of water and fertilizer and in combination with high capture efficiencies (85–95%) could reach the extraction goal of 161 GtC in 2100. While the goal is to reach between 159–189 GtC of net negative fossil fuel carbon emissions, land use and land cover change emissions (as shown in the previous section) might increase and devalue the biomass harvest potentials.

5.3.3 Overall carbon sequestration potentials

Since non-irrigated biomass harvest potentials could not achieve the required extraction levels in the first place, land carbon losses further increase the gap between expectations and realisations (Fig. 5.5 a.). The model spread of land carbon changes (see Fig. 5.3) is still clearly visible and even increased by the uncertainty induced by different levels of CEff. Only if BG are at least partially irrigated and CEff around 75%, the needed lower BECCS levels of 160 GtC could be reached (Fig. 5.5 b., dashed lines). If all BG areas were fully and unlimitedly irrigated even CEff values of 50% could almost achieve net carbon sequestration levels of 160 GtC (with a model spread of 152–197

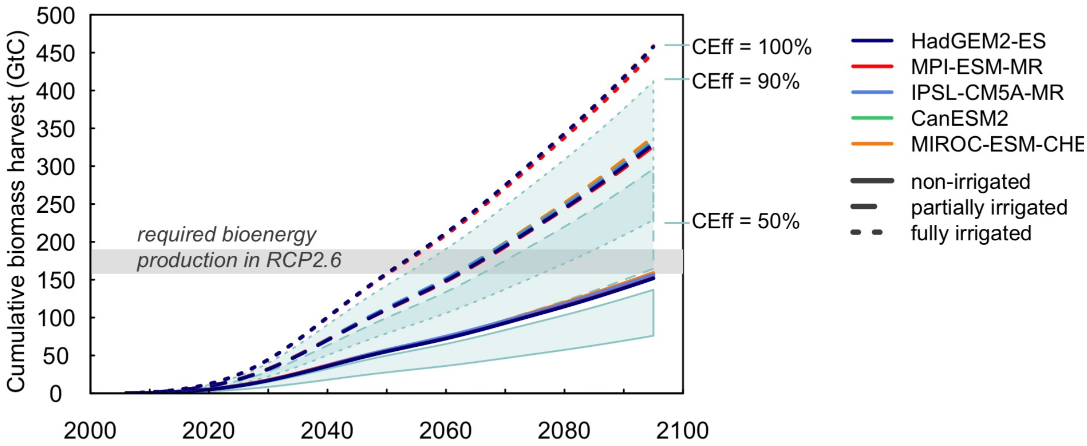

Figure 5.4: Biomass harvest potential in LPJmL. Solid lines depict the actual harvest potential on field (CEff=100%) while shades show the 50% to 90% range of CEff.

GtC, lower edges of shapes). Therefore this analysis also comes to the conclusion that either high irrigation levels, highly carbon efficient pathways or ambitious combinations of both would be necessary to fulfil the BECCS levels given by RCP2.6 (Kato and Yamagata, 2014). Following Rogelj et al. (2015c), 108–216 GtC (with a median of 121 GtC) negative emissions are likely needed to stay below the 2°C target. Whereas if the aim was to even stay below 1.5°C, between 121–270 GtC (median 216 GtC) negative emissions would be necessary until 2100 — with the emphasis on the the major role of BECCS. To achieve these results the areas dedicated to tCDR in RCP2.6 would still require intensive management.

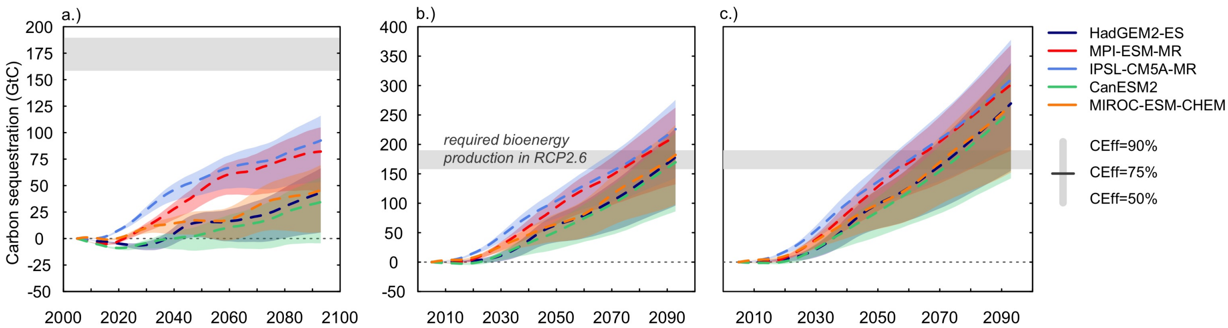

Figure 5.5: tCDR carbon extraction potential for different values of CEff for a.) rainfed, b.) partially irrigated and c.) fully irrigated bioenergy plantations. Shades show the potentials with CEff levels of 50 and 90% while dashed lines represent results for CEff of 75%.

Of course, climate models cause some variability in the results. This uncertainty could be reduced by calculating the sequestration potentials for a wider range of climate models. Although this has not be done so far due to computational expenses, the presented results still capture a possible range of outcomes. One reason for the insufficient potentials could be the unsuitability of the areas chosen for BP by the IMAGE model. But a relocation of BP to more suitable areas would entail further trade-offs. For example, agriculture areas would have to be relocated as well causing transformation of natural land. If this would be done for each climate model input, simulation outputs of tCDR potentials and trade-offs would be less comparable. Furthermore, decision makers would establish BP in locations of land abandonment due to the economic benefits of increasing land use intensities in other regions and rather not due to the climate variability projected by different climate models (if not proven to be statistical significant). Therefore, and to my opinion, it is justified to assess the tCDR potentials of a given, externally generated land-use scenario including BPs provided by the IAM IMAGE.

A further step to increase the overall sequestration would be to investigate bioenergy trees instead of BG. Although BG reach higher biomass harvest levels, the soil carbon development of BT might lead to a better net carbon balance than with BG.

5.3.4 Required food production levels

Food crop and pasture production increases up to 2050 due to spatial expansion before staying rather constant. The influence of climate model inputs is rather small (not shown). Again, the impact of management on the expanding or intensifying agricultural land is of major importance. Partial or complete irrigation substantially increases yields. If these yields are translated to kilo calorie production per capita and day for a rising world population of up to 9.5 bn people in 2050 (United Nations and Affairs, 2015; van Vuuren et al., 2009), yield increase requirements can be derived. The daily intake is based on the FAO calibrated values of 2005 (approximately 3300 kcal cap^{-1} day^{-1} from crops produced on field) and on constant crop mixes and shares of animal products (e.g. linearly scaled pasture extents). Following this approach, 22%, 18% or 13% of yield increases would be necessary in 2050 compared to 2005 for rainfed, partially and fully irrigated crop land expansions, respectively. According to van Vuuren et al., 2009, food crop yields need to increase by 12.5% until 2050 in such a low emission scenario with 9.4 bn people. Either high management input due to irrigation could fulfil this requirement, or options such as changes in dietary trends or genetic modifications would be needed.

5.4 Conclusion & outlook

The preliminary results indicate that: a) the reproduction of the land-use input of RCP2.6 is not clearly documented, b) only highly managed biomass plantations in combination with highly efficient conversion pathways could reach required tCDR levels and c) ambitious yield increases would be necessary to feed a growing world population of 9.5 bn people in 2050 (UN, 2004).

Further investigations and more detailed analyses are needed to give better quantified results on the potentials and trade-offs of RCP2.6. For example, explicit yield increase scenarios could be simulated, water consumption amounts be calculated and biome shifts in response to climate inputs analysed. Also, bioenergy trees could replace bioenergy grasses or BP could be relocated to identify more suitable areas which decrease the management input but induce new trade-off with agriculture or natural ecosystems.

These findings turn this widely accepted mitigation scenario into a similarly unrealistic scenario as found in the previous chapters. Moreover, these results claim for an increased modesty, caution and a realistic reassessment of current mitigation scenarios limiting global mean warming below 2°C.

6 General conclusion and outlook

This thesis demonstrated that tCDR is an inefficient tool to conquer advanced climate change and that the implementation of BPs would induce negative impacts on the environment and human well-being. tCDR is found to be inappropriate to interrupt the trend of increasing carbon emissions and continuous land-use and land cover change that has been prevailing our planet since the beginning of the Anthropocene. These findings are mostly independent of spatial scales, background emissions and time of operation — and, thus, independent of the definition of tCDR as a CE or mitigation tool. Exceptions could be the restoration of degraded or very unproductive soils with BPs, drastic changes in future diets or crop management releasing land for BPs or technological innovations leading to very efficient carbon utilization pathways.

Therefore, the presented work substantially reduces some of the uncertainties that motivated this study in Section 1.4 of the introduction. The following section will summarise the main findings, illustrate further needs for research and elaborate upon remaining uncertainties.

6.1 Answers to the underlying research questions

Indeed, Chapters 2-5 give satisfying answers to the initial research questions regarding the feasibility of tCDR in the future.

Is the tCDR potential of BPs sufficient to lower, balance or even overcompensate different levels of future emissions?

No. The potential of tCDR as a CE method at any spatial scale would not be sufficient to balance unabated emissions in the future if BPs were established not before the 2°C is reached around 2050 (see Chapter 2 and Fig. 6.1 first study case). Even the conversion of the most productive quarter of current agricultural (2.2 Gha) or natural land (3.3 Gha) could delay 2100's emissions budget of in total more than 2000 GtC by only two to three decades (equivalent to ≈550–800 GtC extraction potential if conversion efficiencies of biomass were assumed to be about 50%), respectively. These BPs would rather induce severe trade-offs for food production and ecosystems that might be challenged by climate change impacts and population growth simultaneously (see next research question and Fig. 6.2). This study enlightens the maximum limits of tCDR applied as a CE method in the sense defined in the beginning (Section 1.4).

Despite converting major parts of the land surface to BPs, biomass allocation and subsequent carbon extraction pathways could not achieve satisfying results even if implemented when the 1.5°C is reached (around 2035, see Chapter 3). Only if emissions from the main drivers, fossil fuel combustion and land-use and land cover change, would be reduced at the same time BPs could possibly assure that GMT changes stay within the 2°C or even the 1.5°C guardrails (see Fig. 6.1 second study case). For example, similar BP scenarios as mentioned above (25% of the current agricultural or natural land transformed to BPs) would extract ≈500–800 GtC until 2100 postponing 2100's partially-mitigated cumulative emissions of about 1300 GtC by six to eight decades. However, these tCDR scenarios would entail similar trade-offs as shown in the first study.

If land availability was, as a logical consequence of the previous findings, constrained by food production, ecosystem conservation as well as climate protection, tCDR potentials would be strongly limited despite reduced background emissions as in the previous analysis (see Chapter 4 and Fig. 6.1 third study case). This holds even though land availability is tested earlier, in 2020: the here assumed yield increases of up to 1.40% yr^{-1} on today's agricultural areas could not provide an overproduction of food (based on the current diet) for a growing world population of over 7.5 bn people in 2020 or 9.4 bn in 2050 and thus, not free land for BPs. Transforming therefore natural land to BPs, tCDR potentials could be as high as 91 GtC from 2020 until 2100 if all shrub and grass land were converted to BPs leaving forests and protected areas untouched — but still at the expenses for ecosystems. The restoration of severely and extremely degraded soils (≈300 Mha) with BPs could, however, achieve about 67 GtC until 2100.

Even the realisation of the commonly used RCP2.6 reveals discrepancies between the expected and the achievable tCDR potentials. Only high management inputs (e.g. irrigation water and fertilizers) and conversion efficiencies up to 90% (e.g. carbon losses along the carbon utilization chain stay around 10%) could possibly fulfil the high expectations of 160–180 GtC tCDR potential (see Chapter 5 and Fig. 6.1 foruth study case).

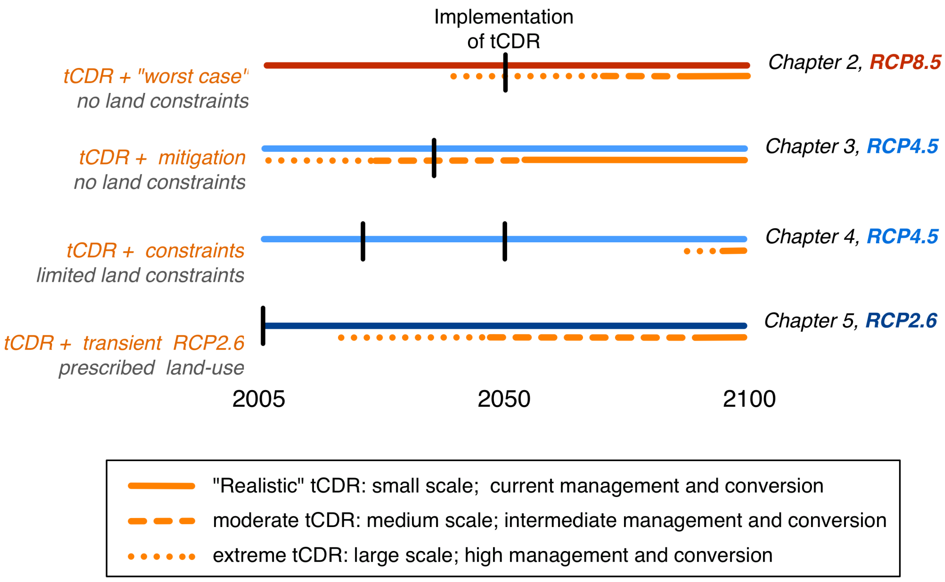

Figure 6.1: Illustration of tCDR potentials calculated in this thesis' analyses. While the red and blue horizontal lines indicate the total carbon emissions following the background emissions scenario, the orange lines indicate the tCDR potential (in GtC or years saved) for given spatial scales or, in case of RCP2.6, management and conversion options. The vertical black markers point at the time of implementation of BPs as shown in Fig. 1.3.

Overall, tCDR, neither as a CE method (Chapters 2-4) nor as a mitigation tool (Chapters 4-5) could produce satisfying, that is, sufficient carbon extraction potentials to slow down or reverse the atmospheric carbon loading responsible for an increasing GMT. These results are schematically presented in Fig. 6.1.

What would the trade-offs for food production and the impacts on climate and ecosystems be?

There is always a trade-off between the establishment of BPs (or any other alternative) and the purpose of the original land cover (see Fig. 6.2).

Agricultural land supplies the human world population with food and fibre. With the prospect of a growing world population, dietary trends, unknown yield increases and possible climate change impacts on crop production it is difficult to rededicate land for the establishment of BPs. Transforming any agricultural land for the purpose of tCDR would restrict food production, might cause a local temperature changes through albedo changes and lead to increased nitrous oxide emissions from fertilizers. For example, the conversion of 25% of the most productive agricultural areas to BPs would lead to a

Figure 6.2: Illustration of the impacts and trade-offs of large-scale BPs for the purpose of tCDR. As described in this thesis BPs can change the albedo of the surface, water fluxes through vegetation changes or induce additional emissions. Trade-offs were identified for food production, ecosystem protection and water supply.

reduction in current food production of almost 75% and a doubling of the current nitrogen application. In fact, the model was not able to provide enough food for an expected world population of 9.5 bn people in 2050 with the current agricultural land extent, diets and an annual yield increase of 1.40% yr^{-1}. Thus, every appropriation of currently cultivated land for tCDR would increase the already existing pressure on yield increases, new diets or agricultural land expansion.

Natural land serves as a habitat for animals and hosts the majority of terrestrial biodiversity. This diversity ensures resilience of ecosystem. Humans are further attached in an emotional way to these landscapes. But natural land also regulates our climate through moisture, heat and momentum fluxes and, of course, partially offsets anthropogenic annual emissions. A conversion of these carbon rich areas to monocultural BPs would not only cause land cover change emissions, but also a loss of biodiversity and resilience and certainly an alteration of atmospheric properties. For instance, the conversion of 25% of the most productive natural area would reduce the global forest to one third of its potential historical extent but increase evaporative fluxes on this area by almost 60%. Furthermore, the conversion of all shrub and grass land to BPs would lead to a loss of currently protected areas (e.g. biodiversity hotspots) of almost 20% if they were not explicitly excluded.

Could natural vegetation capture similar magnitudes of carbon?

Not really. BPs are highly managed for the purpose of effectively extracting carbon out of the atmosphere. This is done by regular harvests followed by effective carbon conversion chains that minimise carbon losses.

The potential of natural vegetation in comparison would be reduced by one third of the potentials achieved by BPs in the first analysis for hypothetical scenarios (see Chapter 2). This is due to variety of possibly less productive vegetation regrowing on this land and the decrease of productivity with maturity. Although natural afforestation projects might need less maintenance and thus, might cause less emissions by fertilizers and harvest losses, similar trade-offs as with BPs would occur due to their need for space.

Is there enough land available for the establishment of BPs?

This depends on the priorities. As indicated before, constraining land availability by trade-offs such as with food production or biodiversity protection would reduce the tCDR potential. The reason is that less to very little land could be released for BPs (see Chapter 4). Recent studies and this analysis found it to be nearly impossible to feed a growing world population (presumably with increasing demand for space consuming animal products) and simultaneously protect all natural ecosystems (Powell and Lenton, 2012; Kraxner et al., 2013; Bajželj et al., 2014). If the aim was to extract as much carbon as possible to limit climate change, any land could be released for the establishment of BPs — with subsequent consequences (see Chapters 2 and 3). Each conversion of land could be bought at the price of the above described trade-offs and impacts. Thorough trade-off analysis and assessment would be necessary to decide whether land could be made available for the purpose of tCDR.

However, one possibility could be the restoration of degraded or very unproductive agricultural land (see Chapter 4). Although the underlying maps of degradation are outdated after 25 years (there might even be more degraded soils today; no new data sets available) and the value and definition of degraded land are both still under debate, these areas could be regained under sustainable management. This study only investigated non-irrigated BPs, but irrigation and the right choice of bioenergy plant species could probably restore those soils as local field studies e.g. in China indicated (Xie et al., 2013; Qin et al., 2011).

Could technological development save space and time through an increase of efficiency?

Possibly. This study only provides estimates of current and future carbon conversion efficiencies and no detailed life cycle assessment (as given by e.g. Edenhofer et al., 2011; Lenton, 2010; Kato and Yamagata, 2014; Tilman et al., 2006). Depending on the chosen conversion pathway efficiencies (i.e. the amount of carbon permanently captured) may vary between 20 to 90% and likely be around 50% for large-scale applications (see Chapter 4). We cannot foresee future innovations. However, the results indicate that if conversion efficiencies rise substantially due to technological development less space might be needed to extract one unit of carbon compared to a standard setting (50-60% less). If furthermore very fertile land is taken, spatial and temporal requirements on BPs could possibly be further reduced.

Of course, innovations in food production and global trade (Godfray et al., 2010; Foley et al., 2011) could also make land available for the purpose of tCDR. If aquacultures became popular (Kovač et al., 2013; Enzing et al., 2014), artificial meat and dairy production replaced our animal products (Tuomisto, 2010) or genetically modified super crops saved land (Bennett and Jennings, 2013), enough land could be released on formerly managed agricultural land for the establishment of BPs (although this development is uncertain, Tilman et al., 2002; Alexandratos and Bruinsma, 2012).

6.2 Remaining uncertainties: perspectives for future research

Although the research questions could be answered satisfactorily, some uncertainties remain. These may be inherent to the methods used in this study, emerged during the analysis or could not be approached in the first place.

Some simplifications restrict our results such as the approximated utilization chain of biomass that governs the amount of actually sequestered carbon from the atmosphere, the instantaneous establishment of BPs at a large-scale or the unlimited nutrient supply. Although these limitations make our results rather optimistic, tCDR potentials remain insufficient to limit climate change. In fact, a more realistic implementation phase over e.g. 20 years would not substantially increase the potential. If the presented tCDR scenarios were gradually introduced (“ramped up”), overall potentials would decrease (tested but not shown) while in the end, the trade-offs for food production and ecosystems would still remain severe since the same amount of land would eventually be affected. Adding a tCDR ramp prior to the suggested points of implementation in our studies would not increase potentials much, e.g. only by some years since the annual potentials were insufficient in the first place — while the impacts continue to increase.

One might assume that a more detailed representation of the biomass conversion pathways could add some confidence in the results. However, the results envelope a sound range of possible conversion efficiencies found in literature - independent by which explicit technique they could finally be realised.

The underlying tCDR land-use scenarios are simplified but systematic and allow for a general understanding of the limits of tCDR. Even though RCP2.6 is seen as a realistic scenario as it has been widely used since its publication, it is not more realistic or probable than other scenarios used in the presented studies. There might be strong non-linearities in the behaviour of ecosystems, biodiversity and, especially, human behaviour. Nevertheless, educated guesses and proposals can be created that draw a map of possibilities. Therein, some of the more extreme tCDR scenarios may fall in very unlikely regions while others cannot be ruled out per se. Overall, this study aimed at investigating the potentials and trade-offs of tCDR and succeeded using the created tCDR land-use maps.

Based on the confidence in the model's capability to simulate vegetation patterns, managed land including BPs and biogeochemical cycles, the here presented studies deliver carbon extraction potentials of tCDR in the right order of magnitude. Regardless of limitations mentioned above — which may classify the potentials rather too optimistic — the ability of tCDR to balance, stop or reverse future carbon emissions is very limited. As pointed out by Heck et al. (2016) field studies on BPs are mostly located in Europe and the US. Field studies in other world regions would be welcome to adjust the model's behaviour. However, LPJmL aims at representing global average production rates and meets this requirement.

Future studies could also focus on the restoration of degraded soils by testing different plant species and management practices. Based on recent field studies the effectiveness of, for example, the Jatropha plant could be tested which is assumed to grow on degraded soils, provides for bioenergy and leaves space and shade for food production in between the plants (Francis et al., 2005; Wani et al., 2012). Especially in this context, but also in general, the effects of irrigation of BPs on the water cycle remain to be studied (e.g. water demand and supply and moisture recycling).

Also, our study did not include sustainable management with mixed cultures, irrigation or natural fertilisers like biochar (Woolf et al., 2010; Crombie et al., 2014; Smith, 2016). For applications at reasonable scales, these investigations might be informative.

Further, fully coupled simulations would be needed (still, with a detailed representation of land processes as in this study) to capture, especially, biogeophysical and ocean feedbacks (see e.g. Zickfeld et al., 2016). Until now, only coarse models of intermediate complexity calculate the ocean and atmospheric responses to CDR strategies by implementing and invisible negative carbon pool or very simplified vegetation processes (Lenton and Vaughan, 2009; Keller et al., 2014; Zickfeld et al., 2016). Adding sophisticated land surface and carbon processes could give insight to more complex feedback mechanisms and thus, a better understanding of tCDR potentials and trade-offs. If such simulations could be conducted, the importance of carbon utilisation chains becomes more important, since they govern the net carbon extraction potentials. tCDR, carbon utilization pathways and ocean feedbacks affect the atmospheric CO_2 concentration and biogeophysical effects regional temperature patterns. The representation of these effects would therefore complete this study regarding the (positive and negative) temperature benefits possibly arising from the implementation of tCDR.

In the course of my literature research it became obvious that there is a gap of perception regarding tCDR between the communities of vegetation and Earth system models and integrated assessment models. IAMs often use land models only for the initialisation and scaling factors thereafter due to the calculation at scales of world regions (e.g. Lotze-Campen et al., 2010; Humpenöder et al., 2014). This might cause discrepancies between the assumptions made on the capabilities of the land to supply tCDR levels that might not be given if the land model was driven by the land-use patterns derived by the IAM (see RCP2.6, Chapter 5). A closer link between both communities could achieve a broad consensus about tCDR potentials on the one side and scenario assumptions, e.g. land-use patterns driven by socio-economic factors, on the other side.

6.3 Final remarks

This thesis takes an important step forward in understanding of the potentials, trade-offs and impacts of BPs for the purpose of tCDR from an Earth system analytical point of view.

The future holds countless possible pathways open. Climate, socio-economic and land-use scenarios just illustrate which possible ways human kind and the climate system could follow. This thesis only maps a few scenarios in this wide space of possibilities: at the margins with extreme (tCDR as a CE method, see Chapters 2 and 3) and in the middle using strictly constrained simulation experiments (tCDR as a mitigation option, see Chapters 4 and 5). The span covered by the presented results indicated that tCDR is not efficient at any spatial scale if emissions continue to rise and that the trade-offs and impacts are severe. The massive use of tCDR would be yet another way of changing the planet's surface — maybe with different characteristics and motivations than for the Neolithic revolution but with similar consequences for the environment, climate and human well-being.

Engineers approach a new task by describing the problem, identifying the causes, evaluating each possible solution and, finally, developing the best option to solve the underlying task. The challenge here is climate change and its impacts on human well being and ecosystems. The causes are human-made emissions from mainly fossil fuel combustion and land-use and land cover change. The solutions could therefore be rapid emission reductions - or climate engineering proposals such as tCDR. I here demonstrated that the latter is no option since the negative implications overrule the benefits by far. But also other CE methods are found to be ineffective or too risky to apply (e.g. Keller et al., 2014).

Therefore, the consequences derived by the results of this thesis certainly comprise that rapid mitigation of climate change through the replacement of fossil fuels with renewable energies is inevitable. Further options could be the reduction of waste to increase recycling mechanisms could decrease the dissipation of resources and thus, fossil fuel extraction. The answers could also lie in sustainable management of land, regionalisation of food production or in the globalised trade of food produced in concentrated areas or world wide changes in diets. Innovations have accelerated over the past decades and chances are high that smart and effective technologies might soon be developed that save emissions without decreasing but rather increasing our standards of living.

I like to conclude this thesis with the remark that the presented results should not be perceived as depressing or hopeless. They should rather be taken as thoughtful advice for the development of future emission scenarios or mitigation incentives. Biomass plantations cannot solve the problem of climate change but continue to exploit natural resources. They can only add a small share to the mitigation pledges on very selected land areas with the caution to prevent negative impacts from its application. There is still time to find, pursue and promote alternative mitigation options before even discussing the implementation climate engineering proposals. The discourse on and research of CE methods is vital to provide the public and decision makers with educated information on the potentials and risks. This thesis contributes substantially to this attempt by reducing much of the persisting uncertainties regarding tCDR. However, decisions on alternative mitigation pathways have to be made in the very near-future and the Paris agreement was just one of many important steps forward.

A Supplementary material to Chapter 2

Supplementary material to Paper1 as published.

For the manuscript *Limited potential of terrestrial climate engineering to delay Earth's anthropogenic warming* by Boysen et al. initially submitted to Science Advances.

July 2016

Materials and methods

A.1 Description of the model LPJmL

Nine plant functional types represent (potential) natural vegetation in the dynamic global vegetation model LPJmL (Sitch et al., 2003; Bondeau et al., 2007). They compete for light, water and space under prescribed monthly fields for temperature, precipitation and cloud cover and annual data on atmospheric CO_2 concentration and soil conditions. The monthly observation datasets are disaggregated (Gerten et al., 2004) to allow computation on a daily time step level on a 0.5 times 0.5 degree grid. Plant mortality is governed by fires, heat and water stress and growth efficiency. Cultivated land is represented by 12 crop functional types and pasture lands (Bondeau et al., 2007), which are located on the historical agricultural land until 2005 as described by Fader et al. (2010). Crop management is calibrated to meet current (1995–2005) country-level yields per crop type as reported in FAO statistics, following the procedure described in Fader et al. (2010); due to lack of data such a calibration is not performed for the bioenergy plants considered herein (see below).

The overall performance of LPJmL has been successfully evaluated against observational data in studies for e.g. net primary production (Cramer et al., 1999), runoff (Gerten et al., 2004), crop yields (Bondeau et al., 2007; Fader et al., 2010) and bioenergy yields (Beringer et al., 2011). In comparisons among dynamic vegetation models LPJmL results are often found to be located at a medium position (Gerten et al., 2004; Friend et al., 2014; Nishina et al., 2014). The simulation of global living biomass is well represented compared to literature estimate as shown in Fig. 2.1 B and the literature sources can be found in Table A.1.

Table A.1: Literature underlying biomass data shown in Fig. 2.1B.

Study	Carbon (GtC)
IPCC AR5 CH6 Fig. 6.1 p. 471 (Intergovernmental Panel on Climate Change, 2014)	450–800
Prentice et al. (2001)	466–654
Smil (2003) (Table Appendix E, p. 283, 10%/ 90% percentile taken)	490–819 (of 486-–1395)
Lal (2008)	500–650
Poulter et al. (2015) (Satellite data)	512–606
Anav et al. (2013) (19 CMIP5 models)	335–927
LPJmL simulations (mean 1995–2005)	606—782 (with and without land use)

A.1.1 Biomass plantations in LPJmL

The model represents three types of second-generation biomass plantations (Beringer et al., 2011). Woody biomass plantations are represented by the characteristics of poplar and willows for temperate regions and *Eucalyptus* for tropical regions. They are simulated to be harvested every eight years and clear-cut after 40 years. During harvest 65% of the sapwood and 50% of the heartwood are taken and put into a harvest carbon pool. Herbaceous biomass plantations are represented by the properties of the fast-growing grass types *Miscanthus* and switchgrass. In contrast to Beringer et al. (2011), these grasses are assumed to allocate carbon on a daily basis and to be harvested as soon as 400 gC m^{-2} are reached whereby 85% of the above-ground plant material is taken away. Also, bioenergy trees are now parameterised to be more resistant to water stress (through higher rooting depths).

The distribution of BG and BT depends on the best net outcome of biomass harvest and land carbon changes by the end of the century. The resulting global distribution is shown in Figure A1.

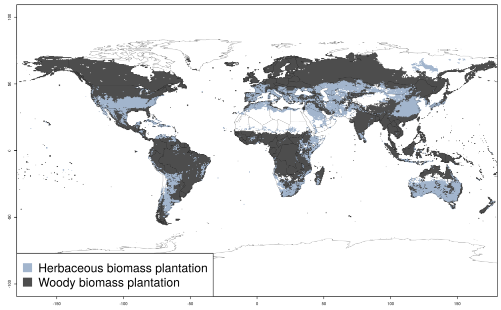

Figure A1: Global distribution of bioenergy grasses (BG, bright grey) and bioenergy trees (BT, dark grey).

A.1.2 CO_2 fertilization effect in LPJmL

Increasing CO_2 levels lead to a fertilization' effect of the global vegetation. Figure A2A depicts tCDR potentials for different scenarios and three different climate projections aiming at 1.5K, 2.5K and 4.5K in 2100 with corresponding atmospheric CO_2 concentrations of 390ppm over 546ppm to 1050ppm (Heinke et al., 2013). tCDR plantations on natural land (25FN and 10FN) as well as on agricultural land (25CP and 10CP) increase productivity by 27–32% due to the CO_2 increase from 390ppm to 1050ppm and a preferential climate. Reforestation of crop lands (25CP pnv) experience a 3% increase whereas permanent forests (25FN pnv) even increase by 9% since long established tropical trees strongly increase in productivity and temperature increases in higher latitudes favoring plant productivity and longer growing seasons. The higher productivity of BP in a BAU scenario (1050ppm) compared to a low emission scenario (390ppm) is mainly caused by the elevated CO_2 concentrations. Fig. A2B shows, that the CO_2 increase of 660ppm causes a BP potential increase of about 30% whereas the climate effect only adds 2–6%. Natural vegetation is less sensitive to CO_2 fertilization than BPs.

Previous studies estimated ca. 20–30% higher productivities of woody biomass plantations at CO_2 concentrations of 488—532 ppm (B1 to A1B scenarios in 2050, Beringer et al., 2011) depending on the emission pathway (Leipprand and Gerten, 2006; Luo et al., 2008). However, since nutrient limitations are not explicitly considered in the model, our estimates of this beneficial CO_2 effect—thus of the tCDR potentials—are still rather at the optimistic end.

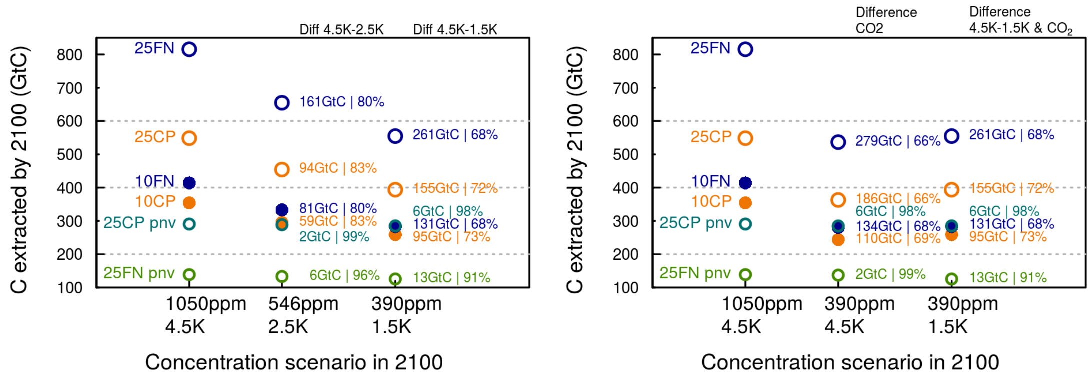

Figure A2: LPJmL-simulated biomass plantation and natural vegetation productivity in dependence of different CO_2 concentration and temperature levels in 2100. (left) Comparison of different climate scenarios and (right) contribution of climate and CO_2 separately.

A.1.3 Comparison of simulated yield with field studies

Figure 1C presents LPJmL's performance in simulating biomass plantation at locations for which field studies could be found in literature. These field studies should rather not be taken as basis for a model validation since their growing conditions and management options usually represent very intensively managed systems. Many studies are established on preferable ground with good management options and only on small plots, while our model — uncalibrated and forced by global-scale input data — simulates large-scale potentials not meant to be representative on the small scale. In Fig. 2.1C we aim at representing highly productive second-generation bioenergy plants and therefore neglect study and model results showing yields lower than 5 odtC/ha (oven dry tons). Cells with too little biomass harvest are not considered for tCDR (see Table S2). This results in a total of 54 and 31 comparable sites for herbaceous and woody bioenergy plantations, respectively. While the simulation results for herbaceous biomass plantations are generally satisfying, the results for woody biomass plantations show some deficiencies, i.e. mostly underestimated model yields in tropical regions. However, the number of studies is very limited and the general representation of tropical biomass plantations shows higher yields than in these very plots. All studies and the according LPJmL results are listed in Table S2 and are discussed in depth by Heck et al. (2016).

A.1.4 Changes of biogeophyical properties in LPJmL

Moreover, as the detailed representation of the terrestrial carbon cycle is the strength of this model, climate feedbacks due to land-use and land cover changes in response to e.g. albedo changes (Arora et al., 2011; Pongratz et al., 2011; Brovkin et al., 2013), are not represented. In the following we roughly estimate the possible effects of albedo and moisture flux changes on climate.

Bioenergy plantations tend to have lower albedo values (Schaeffer et al., 2006; Caiazzo et al., 2014) than agricultural plants but higher values than natural vegetation (Pongratz et al., 2011) as calculated by our model (Forkel et al., 2014). Consequently, the overall signal is therefore a significant cooling, if natural lands were replaced by tCDR plantations, and a warming if cropland or pasture land were replaced. Overall, the estimated changes are larger than past land-use change induced alterations of albedo (Pongratz et al., 2011) but of opposite sign (and only comparable at very local scales (e.g. past land-use change in India; This is partly explained by the more detailed representation of agricultural and natural land in our study compared to Pongratz et al., 2011). Therefore, albedo effects could indeed have a significant impact on estimated temperature changes after the establishment of tCDR plantations. Contrarily, other studies find an overall cooling effect of herbaceous bioenergy plants on former cropland (Merlin et al., 2013; Davin et al., 2014). They indicate that the sign and magnitude of albedo changes strongly depend on the original land cover (e.g. longer growing seasons lengths of BP shade dark soils), the management of crop land and BP (e.g. tillage revealing dark soil versus no-tillage with remaining stubble), snow cover effects (e.g. masking of snow through standing biomass) or even model parameterizations. For example, while LPJmL captures the effect of crop and BP residues, it uniformly assumes an albedo of 0.4 for soils, which is rather high for agricultural lands in the mentioned studies. Comparable large-scale studies on land cover conversion and its impact on radiative and moisture fluxes (including the ocean response) are given by Davin and de Noblet-Ducoudré (2010), Bathiany et al. (2010), and Arora et al. (2011).

According to our simulations, evapotranspirative fluxes change little if 25% of agricultural (+9%) or natural (+12%) land are replaced by tCDR plantations. Contrarily, transpiration increases strongly on agricultural land (+37%) due to higher sapling density, deeper roots (bioenergy trees) and greater leaf areas (bioenergy grasses) reducing soil evaporation (-75%). The changes on natural land are less pronounced with no changes in transpiration but strong increases in evaporation (84%) due to competing effects of transforming partly dense natural forest to highly productive but less dense bioenergy tree plantations or the replacement of less productive shrubs with bioenergy plantations.

A.2 Study set up

A.2.1 Scenario creation

The most productive grid cells on natural and agricultural land were prioritized for conversion to create the 25% and 10% conversion scenarios. For the standard set of simulations depicted in Fig. 2.2 these were cells with the highest net outcome of biomass harvest yields and carbon losses due to emissions from land use and land cover change. In additional scenarios, we also selected cells based on their biomass harvest potential only, as would be the case if e.g. the incentive for tCDR was driven primarily by economic considerations (special case "25% agric. chosen by highest harvest" in Fig. 2.2).

In each scenario, the areal fraction of either agricultural or natural land were assumed to be covered by either herbaceous or woody biomass plantations depending on which of the two is more productive. In the scenarios of agricultural land conversion, 25% (10%) of the most productive crop land and 25% (10%) of the pasture land cells were selected and then combined. Similarly for the conversion of natural land, 25% (10%) of the most productive cells of each major biome (tropical, temperate, boreal and tundra vegetation as well as grasslands) were chosen and then combined (double counting was avoided) to value each biome equally. The resulting scenario distributions are displayed in Fig. A3.

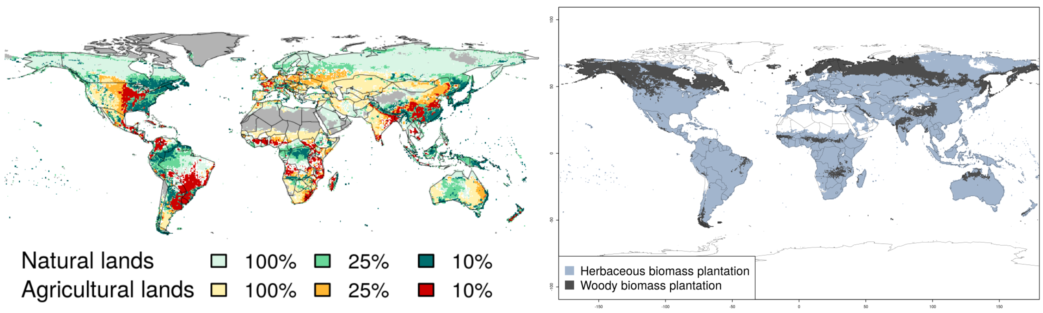

Figure A3: (left) 0.5° grid cells chosen according to highest biomass harvest only (similar to Fig. 2.2). Note that only the dominant share of either agricultural or natural land is displayed within a cell. (right) following Fig. A1.

A.2.2 Simulations carried out

The model averages the carbon pools within each grid cell over all land use and land cover shares at the end of each simulation year and thus, separate global simulations are needed for each land cover type to disentangle their contributions to the mean carbon level of each cell. Therefore, five simulations of potential natural vegetation (fractional areas developing dynamically in response to climate), woody and herbaceous biomass plantations (prescribed according to our scenarios), pastures and cropland used areas (both fixed at year 2005 state) were conducted. Each of our scenarios including tCDR was created by selecting the required shares in each grid cells from these global LPJmL simulations to calculate the carbon balance of tCDR plantations, agricultural and natural land separately.

A.2.3 Starting point of tCDR

The tCDR simulations started in 2047, the year when a global mean temperature increase of 2 °C above preindustrial is crossed on a RCP8.5 trajectory, and continue until 2100. This point was identified by multiplying the cumulative carbon emissions given by Meinshausen et al. (2011) with a TRCE value (see below) of 2°C/TtC which is similar to the T/C ratio (see below) in the underlying IPCC Fig. SMP10 displaying a multi-model mean of RCP8.5 (Stocker et al., 2013b) . But according to the here used climate forcing (aiming at 4.5°C of warming around 2100; Heinke et al., 2013), the 2°C target is reached in 2053 which is why we extend our simulations up to year 2107 and shifted the potentials backward to that earlier year to capture the effect of climate and CO_2 right Simulations under a mitigated climate reaching 2.5°C in 2100 (RCP4.5) were also carried out for the period 2053–2107 although this RCP only reaches 1.8°C of warming in 2047 following the method described above.

The model was spun up for 5000 years to achieve a soil carbon equilibrium in permafrost regions and then for another 390 years to account for effects of land use changes on the carbon balance (Schaphoff et al., 2013). Calculations then started in 1901 for transient simulations under historic land use patterns until 2005 whence land use patterns were held constant until 2053. The prescribed climate scenario was provided by a single climate model (MPI-ESM) from CMIP3 simulations (Heinke et al., 2013), but sensitivity studies with other model inputs showed similar results (data not shown). Model outputs of carbon pools (litter, soil and vegetation and cumulative harvest pools) were smoothed with a 10-year running mean filter (16-year running mean for woody biomass plantations to cover two complete harvest cycles). To account for leakage rates, we only consider 50% of the harvested biomass to be stored permanently (Lenton, 2010). The same holds for the vegetation carbon stored on natural land replaced by biomass plantation.

A.2.4 Delaying carbon emissions with tCDR

The calculation solely depends on the carbon extraction potential of tCDR compared to the cumulative emissions of RCP8.5. Subtracting carbon sequestration potentials off the RCP8.5 value in 2100 leads to the years that this target would be postponed. Similarly to the other RCP pathways, the trajectory would be condensed without actually leaving the emission pathway. Since CO_2 concentrations are kept on the business-as-usual trajectory, no ocean feedback is included in response to tCDR, although variations the partial pressure of CO_2 have already been included in the calculations of the coupled climate model providing the climate forcing for LPJmL.

A.2.5 Global mean temperature potential of tCDR

As described in the main text, the ratio of temperature-to-carbon changes (T/C ratio) in 2100 is needed to transfer tCDR carbon potentials to corresponding temperature potentials by multiplying both. Similarly, the concept of the transient response to cumulative emissions (TRCE, Gillett et al., 2013) is applied to the carbon potentials of simulations forced with climate data from three additional climate models (MIROC3.2 (hires), UKMO HadGEM1, IPSL CM4 and MPI-ESM as in the standard set-up, Heinke et al., 2013). The model response and the TRCE range of 0.7 to 2.0°C/TtC (°C per trillon tons of carbon, Gillett et al., 2013) cause a broad range of estimated GMT changes (Fig. 2.3). We can estimate a potential climate benefit from tCDR however without accounting for possible non-linear feedbacks as described by Brovkin et al. (2013).

A comparison of the effect of different climate model inputs on the tCDR potential in LPJmL is shown for a selection of scenarios in Fig. A4. The larger the scenario area is, the stronger the impact of different models on the potentials. Especially precipitation patterns differ between models (Heinke et al., 2013) causing deviations in the results. However, variations are small and the choice of the MPI-ESM climate forcing as a standard setting seems justified.

A.3 Calculation of the impacts of tCDR

Since we cannot provide a thorough analysis of future agricultural and technological projections here, we simply calculate some possible consequences of turning today's agricultural land to tCDR plantations. Based on calibrated crop yields and assuming

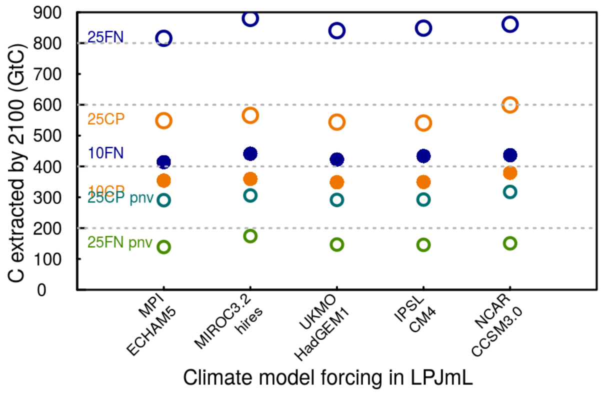

Figure A4: Comparison of the potentials of different tCDR scenarios using five different climate model inputs. MPI-ECHAM5 serves as standard climate forcing for this study.

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a world population of 7 billion people we calculated the amount of calories (Wirsenius, 2000)available per capita and day (after production on the field) if the food was distributed equally over the globe. The current production thus is estimated with 3,038 kcal cap^{-1} day^{-1}. This does not include the transformation of produced feed calories to meat or dairy calories and therefore we only give percentage changes.

Based on the concept of "planetary boundaries" (Steffen et al., 2015) we quantify the impact of further reductions of natural forest cover brought about by tCDR plantations. The land-system boundary defines thresholds of remaining forest extent for three continental forest biomes (boreal, temperate and tropical). We used this approach according to the fractional forest areas provided by LPJmL. Thereby we could analyse the relative change of area in our scenarios and calculate the position with respect to the planetary boundary for land-system change.

The estimated nitrogen (N) content in the harvested biomass gives a first indication of how much N would be needed as fertilizer since plant growth in our model is not limited by N supply. We assume N contents for both herbaceous and woody biomass of 5kg tC^{-1} dry mass. Literature indicates approximation for Miscanthus/switchgrass of 4.9 gN kg^{-1} (Pennington, 2012), 4.8 gN kg^{-1} (mean over range, Karp and Shield, 2008) and for poplar/willow values of 5 gN kg^{-1} (mean over range, Karp and Shield, 2008). We assumed a carbon content of 45% (Kato and Yamagata, 2014) and 50% (Lenton, 2010; Powell and Lenton, 2012) for herbaceous and woody biomass, respectively. Applying this to our model output, herbaceous and woody biomass plantations on all current agricultural areas result in 56 kgN ha^{-1} yr^{-1} and 30.79 kgN ha^{-1} yr^{-1}, respectively. Following Karp and Shield (2008) (50kgN ha-1 yr-1 for switchgrass, 30-80kgN ha^{-1} yr^{-1}

for willows), Kering et al. (2011) (120-168kgN ha^{-1} yr^{-1}) and Beringer et al. (2011) (50-70kgN ha^{-1} yr^{-1}), these values lie at the lower end of study results. Since we chose the most productive cells, values increase over-proportionally the smaller the area gets.

Table A.2: Yields from field studies and according model values for biomass plantation types as presented in Fig. 2.1C (after Heck et al., 2016).

Miscanthus				
Reference	Annotation	Field mean (odt ha^{-1} yr^{-1})	LPJmL (odt ha^{-1} yr^{-1})	Rel. deviation (%)
Acaroğlu and Şemi Aksoy (2005)	Irr., sandy/ silt/ clay	12.6	33.32	182
Christian et al. (2008)	Rainfed, previous LU, 14 years, silty clay loam	13.8, 17.3, 13.25, 15.10, 23.15, 32.25	9.05, 10.28, 8.93, 9.05, 14.06, 33.17	83, 80 , 84, 88, 80, 101
Clifton-Brown et al. (2004) and Clifton-Brown et al. (2007)	Rainfed, fert., loam to sandy, marginal	10.5	10.51	100
Danalatos et al. (2007)	Irr., fert. , clay loam, moderare fertile	26.0	36.19	120
Himken et al. (1997)	Rainfed, fert. (not effective)	23.15	12.33	77
Jørgensen et al. (2003)	Sandy loam, high nutrient content, LU, fert.	8.30	9.49	107
Kahle et al. (2001)		10.05, 11.15, 13.00	11.50, 11.50, 12.01	107, 102, 96
Schwarz (1993)	Rainfed, fert., “good soil”	20.95	14.97	86
van der Werf et al. (1992)	Rainfed, fert., intensive car	21.80	11.21	76
Aravindhakshan et al. (2010)	Rainfed, fert., silt, loam soil	12.75	10.24	90
Heaton et al. (2008)	Rainfed, ideal conditions, intensive preparation, saplings	26.05, 39.45, 38.45	13.28, 13.77, 15.73	75, 67, 70
Davis et al. (2014)	Rainfed, fert.	11.85, 15.80, 23.40, 14.95, 13.05	13.77, 16.50, 6.88, 16.54, 18.77	108, 102, 65, 105, 122

Miscanthus				
Reference	Annotation	Field mean (odt ha^{-1} yr^{-1})	LPJmL (odt ha^{-1} yr^{-1})	Rel. deviation (%)
Stričević et al. (2014)	Irr. in first year, fert.	25.05, 15.35	9.47, 7.53	69, 69
Yu et al. (2013)	Different genotypes tested	11.90	22.33	144
Blair et al. (1985)		31.85	33.48	103
Palmer (2014)	Irrigated	18.35, 20.80	24.17, 32.70	116, 129

Switchgrass				
Reference	Annotation	Field mean (odt ha^{-1} yr^{-1})	LPJmL (odt ha^{-1} yr^{-1})	Rel. deviation (%)
Adler et al. (2006)	Rainfed, fert., silt loam	6.85	17.39	177
Heaton et al. (2008)	Rainfed, ideal conditions, intensive preparation, saplings	11.45	13.28	108
Lemus et al. (2002)	Fert., grundy	9.95	12.05	111
Sanderson (2008)	Rainfed, fert., silt loam, agric. land	6.35	15.67	173
Schmer et al. (2008)	Varying fert., “good land”	6.20	5.65	96
Sladden et al. (1991)	Fert., Wickham soil	20.70	25.65	112
Di Virgilio et al. (2007)	Fert., typical Calcaric cambisol	9.70	11.99	112
Sharma et al. (2003)	Irr., fert.	7.30	38.02	310
Lemus (2004)	fertilizer	16.10, 14.40, 17.49, 17.90, 17.80, 14.10	16.33, 17.97, 20.10, 16.55, 17.71, 17.33	101, 11, 108, 196, 100 111

Switchgrass

Reference	Annotation	Field mean (odt ha^{-1} yr^{-1})	LPJmL (odt ha^{-1} yr^{-1})	Rel. deviation (%)
Sanderson et al. (1999)	Irr. at planting, fert.	14.10, 14.50, 9.65, 15.20, 12.65	9.95, 9.55, 9.68, 17.91, 11.85	85, 83, 100, 109 97
Aravindhakshan et al. (2010)	Rainfed, fert., silt loam soil	15.65, 10.24, 83		
Palmer (2014)	Irrigated	20.95, 20.05	24.17, 32.70	108, 132

Poplar

Reference	Annotation	Field mean (odt ha^{-1} yr^{-1})	LPJmL (odt ha^{-1} yr^{-1})	Rel. deviation (%)
Cannell (1980)	Agric. land	7.40, 6.00	7.90, 8.21	103, 118
Dowell et al. (2009)	Irr., no fert., high fertility soil on former fescue pasture	10.35	11.35	105
Hofmann-Schielle et al. (1999)	Fert., agric. land	11.95, 5.65	8.82, 8.94	87, 1129
Laureysens et al. (2004)	Irr. at establishment, heavy clay loam with high nutrient content, former landfill	6.80	12.57	142
Rae et al. (2004)	Irr./ rainfed, varying fert., agric. land	11.82, 7.05	10.62, 6.39	
95, 95				
Berthelot and Gavaland (2015)	Fertilizer	10.0	6.78	84

Willow				
Reference	Annotation	Field mean (odt ha^{-1} yr^{-1})	LPJmL (odt ha^{-1} yr^{-1})	Rel. deviation (%)
Labrecque and Teodorescu (2005)	Rainfed, no fert.	11.55	5.69	75
Linderson et al. (2007)	Rainfed	12.45	7.56	80
Lindegaard et al. (2001)	Varying soil quality	11.35, 9.80, 9.30, 11.15	8.30, 8.37, 9.50, 10.10	87, 93, 101, 95
McElroy and Dawson (1986)	Marginal agric. land	12.9	9.68	88
Scholz and Ellerbrock (2002)	Varying fert., agric. land	5.4	6.39	109
Adegbidi et al. (2003)	Varying fert.	9.65	7.33	88
Demo (2013)	Fert., loam	6.77	5.91	94
Pugesgaard et al. (2014)	Fert., sandy loam soil	5.85	6.90	109

Eucalyptus				
Reference	Annotation	Field mean (odt ha^{-1} yr^{-1})	LPJmL (odt ha^{-1} yr^{-1})	Rel. deviation (%)
Binkley et al. (2003)	Rainfed, fert., volcanic ash, gentle slope, formerly agric. land	14.75	19.83	117
Hunter (2001)	Irr., varying fert., deep lateritic soil	15.35	20.38	118
Laclau et al. (2000)		11.35	8.95	89
Stape et al. (2010)	Rainfed, varying fert., former plantations or grassland	23.25, 23.90, 28.60, 23.90, 18.40, 23.10	5.73, 10.08, 14.74, 13.70, 7.54, 7.54	62, 71, 76, 79, 70, 66

Table A.3: tCDR potentials for the mitigation scenarios under a RCP4.5 climate trajectory.

		Implication	**Potentials in 2100**			
			C extracted (GtC)	C flux (GtC yr^{-1}) (mean)	Years delayed (yrs)	T change (°C)
RCP4.5		Afforestation, reduced emissions	-1227	5	-	2.6 (since 1870)
Agri-cultural land	100%	Limited to	546	9	-64	-1.1
	25%	no food	431	7	-54	-0.9
	10%	production	285	4	-41	-0.6
Natural land	100%	Drastic	1075	19	-132	-2.3
	25%	reductions	631	11	-72	-1.3
	10%	to total loss	320	5	-44	-0.7
Special cases	RCP2.6 + RCP4.5	Dedicated bioenergy + abandoned lands	237	3	-36	-0.5
	25% agric. with NV	Restoration of land with natural vegetation	237	3	-36	-0.5
	100% pas-tures	No meat or dairy production	302	5	-42	-0.6

Table A.4: tCDR potentials for the special case scenarios shown in Fig. 2.3. Results represent potentials in the year 2100 (mean of 2095-2105) after a simulation time span of 53 years (2047-2100).

		Agricultural land with potential natural vegetation			Agricultural land chosen for highest harvest		Natural land chosen for highest harvest
Pixels chosen	100%	25%	10%	25%	10%	25%	10%
C extracted (GtC)	347	291	175	466	301	639	311
C flux (GtC yr^{-1})	5	4	2	8	5	11	5
T change (°C)	-0.8	-0.6	-0.4	-1.0	-0.7	-1.4	-0.7
Time delayed (yrs)	-13	-11	-6	-18	-11	-25	-12

B Supplementary material to Chapter 3

Supplementary material to Paper2 as published.

For the manuscript *Impacts devalue the potential of large-scale terrestrial CO2 removal through biomass plantations* by Boysen et al. submitted to Environmental Research Letters: ERL-102570 July 2016

B.1 Global distribution of BG and BT

The global distribution of both biomass types is the result of their assumed implementation following the highest accumulated annual biomass harvest potential and, respectively, the according changes in carbon pools in 2100 (Fig. B1 left). The bioenergy type with the best net outcome is taken for each cell individually. If the choice is done only regarding the highest accumulated biomass harvest in 2100 without taking carbon changes into account, a different distribution results (Fig. B1 right).

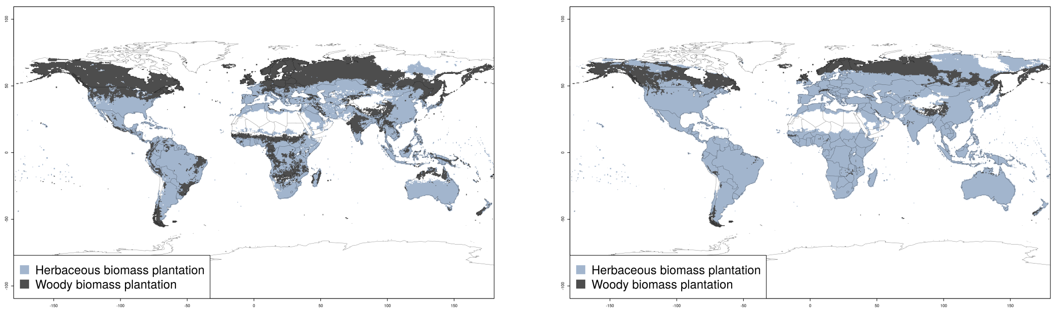

Figure B1: (left) global distribution of herbaceous and woody biomass plantations, (right) the distribution for the choice of cells regarding only the highest biomass harvest.

B.2 Albedo calculation in LPJmL

The albedo calculation in LPJmL follows the procedures from Strengers et al. (2010)and Forkel et al. (2014). Albedo values for crop residues (straw, stubble) have been adapted with a mean value of 0.27 following literature (Horton et al., 1996; Merlin et al., 2013; Davin et al., 2014). BG residues were estimated with 0.32 following Kucharik et al. (2013). Soil albedo in LPJmL is, due to the lack of detailed soil albedo representation, uniformly set to 0.4 which is higher than values given in the above-mentioned publications for agricultural land. However, since the model simulates stubble and crop residues which remain on the field and cover the soil colour, this disadvantage is partly set-off.

Choice of cells for BP

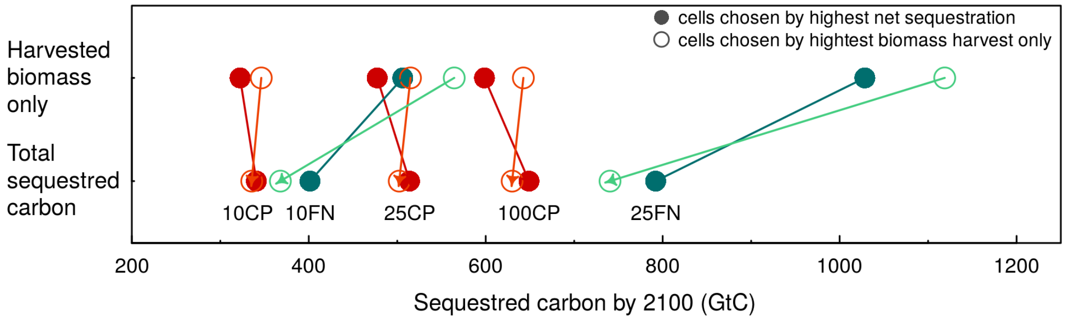

Figure B2: Comparison of the choice of cells for the sequestration potential either with focus of highest harvest only (open circle) or total sequestration potential including land carbon changes (filled circles).

Quantification of impacts on evapotranspiration (ET)

Table B.1: Local moisture fluxes (evapotranspiration ET, transpiration and evaporation in km^3) on the areas considered for tCDR under constant land-use (2005) or BP in the year 2100.

moisture flux	scenario	100AGR	25AGR	10AGR	100NAT	25NAT	10NAT
ET	LUconst	20498	13001	7669	43369	21914	10556
	BP	0%	+6%	+7%	+7%	+8%	+8%
Transp.	LUconst	11386	7655	4609	31640	16141	7894
	BP	+35%	+40%	+40%	+5%	+6%	+6%
Evap.	LUconst	8529	5009	2810	4305	1461	601
	BP	-66%	-77%	-82%	+47%	+58%	+66%

Literature review on tCDR

Table B.2: Literature review on tCDR as explicit climate engineering method, the physical limits and potential areas and large-scale mitigation studies including re- and afforestation projects.

Explicit tCDR				
Reference	Time	Area (Mha)	Potential (GtC)	Annotation
Lenton (2010)	100 yrs	695–1014	68–133	Most realistic available land for afforestation; only on abandoned agricultural land (range over A1b and B2, van Minnen et al., 2008)
	100 yrs	3800–4000	150–900	Without food constraints
	Today-2100	(dedicated bioenergy area) + (695 to 1014)	∼500	Overall potential with natural sink, surplus wood, afforestation on abandoned land, Biochar, BECS (50% capture rate) and reduction of emissions: 4–6 GtC yr^{-1} by 2050, 6–14 GtC yr^{-1} in 2100
Powell and Lenton (2012)	2000–2050	332–686	180–260	Annual carbon fluxes of 5.2 and 3.6 GtC over 50years with bioenergy crops in low and high meat scenarios with high efficiency (low to moderate land-use increase)
Caldeira et al. (2013)	2000–2100	437	100	3% of global land area needed to extract 1 GtC yr^{-1} with biomass energy from managed temperate forests and CCS
Vaughan and Lenton (2011)	Until 2060	4300	165–183	Soil carbon restoration and re- and afforestation until 2060 leading to a reversal of past land-use and land cover change emissions
Heck et al. (2016)	1982–2005	4267	277–309	Year 2005's agricultural land converted to either BG or BT, irrigated on today's irrigated areas, simulations from 1901–2005, compared to carbon changes under land-use
Keller et al. (2014)	2020–2100	1548	131	Afforestation of the North African and Australian deserts under RCP8.5, irrigated.

Physical limits & potential areas				
Reference	Time	Area (Mha)	Potential (GtC)	Annotation
van Minnen et al. (2008)	Until 2100	3850–3990	583, 913	Physical potential: A1b permanent or harvested forest (wherever more effective than baseline land-use scenario)
		3830	858	Physical potential: B2 harvested forest (as in A1b)
		831-1014	93, 133	Social potential: A1b only abandoned agricultural land with permanent or harvested forest (food and nature conservation constraints)
		695	68	Social potential: B2 abandoned agricultural land with harvested forest (as in A1b)
Lambin et al. (2013)	Currently available	445		Worldbank report 2010
		598		This study, retrieved from GAEZ 3.0
		1400		IIASA/FAO prime land that could be cultivated and is not protected but low productive (Alexandratos and Bruinsma, 2012)
		2100		IIASA/FAO 2012 suitable land GAEZ3.0 (3100 Mha suitable, 1000 Mha already under cultivation)

Large-scale mitigation (Re- and afforestation)				
Reference	Time	Area (Mha)	Potential (GtC)	Annotation
Humpenöder et al. (2014)	Until 2095	2773	192	Natural afforestation of pasture and crop lands due to carbon taxes on emissions; 1.21% yr^{-1} yield increase
		508	162	Herbaceous and woods bioenergy for BECCS on food crop land; 1% yr^{-1} yield increase
		2866 = 2566 afforestation + 300 bioenergy	272	1.36% yr^{-1} yield increase

Arora et al. (2011)	Until 2100	1000–2200	120–240	50 to 100% afforestation of historic crop lands between 2011 and 2060; including biogeophysical and biogeochemical climate feedbacks (CO_2 fertilization, albedo and temperature effects, ocean uptake), A2 emission pathway
van Vuuren et al. (2007)	Until 2100	725–940	116–146	Forestry on abandoned land (range B2, B1 and A1b)
Smith et al. (2013b)	50 yrs	218–990	50	Land required to extract 1GtC yr^{-1} (with 2.1GtC yr^{-1} produced) using temperate switchgrass or tropical eucalyptus and depending on harvest and leakage rates
Beringer et al. (2011)	until 2050	142–464		Sustainability requirements for conversion of land (food production, biodiversity, carbon storage)
			28–125	Rain fed
			56–188	Sustainable irrigation from surface run-off
			141–292	Irrigation with renewable water resources
Kato and Yamagata (2014)	2006–2100	415	43–161	RCP2.6's bioenergy areas (83% of 500 Mha agricultural land increase); current fertilizer input and low CCS level to high fertilizer input and CCS level to stay within 2°C target
Edmonds et al. (2013)	2020–2095	570 = 320 unmanaged natural land + 250 dedicated bioenergy land	163–391	Different combinations of CCS and bioenergy levels depending on policies; different CCS and dietary trends to secure feeding 9 bn people on250Mha.
Reilly et al. (2012)	2000–2100	1400	178	Afforestation, avoided deforestation and bioenergy on crop land; simultaneous emission reductions
Smith et al. (2016)	2100	380–700	330	BECCS needed to limit warming to 2°C (3.3 GtCeq yr^{-1})
		320–970	110–330	Afforestation (1.1–3.3 GtCeq yr^{-1})

C Supplementary material to Chapter 4

Supplementary material to Paper3 as submitted.

For the manuscript *Trade-offs for food production, ecosystems and climate limit the terrestrial carbon dioxide removal potential* by Boysen et al. submitted to Global Change Biology. July 2016

Degraded soils

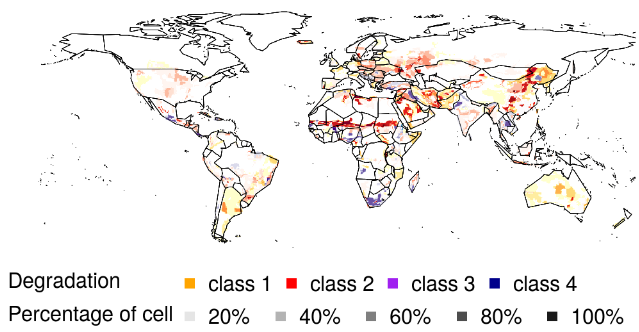

Figure C1: Degradation of soils following Oldemann et al. (1991). Degradation classes 1 to 4 refer to slightly, moderately, severely and extremely degraded soils, respectively.

Table C.1: tCDR potential on degraded land (GLASOD, Oldemann et al., 1991) from 2020 and 2050.

Year	Degradation class*	Area (Mha)	Area not cultivatable without irrigation (Mha)	tCDR potential (GtC) in dependence to CEff		
				20%	50%	70%
2020	1	747	0.09	43	109	153
	2	907	1.44	73	191	270
	3	291	0.00	23	67	96
	4	9	0.00	0	1	1
2050	1	747	0.10	30	74	104
	2	907	1.52	52	129	181
	3	291	0.00	16	44	63
	4	9	0.00	0	1	1

*class 1 = slightly degraded, class 2 = moderately degraded, class 3 = severely degraded, class 4 = extremely degraded.

Maps of albedo and albedo changes

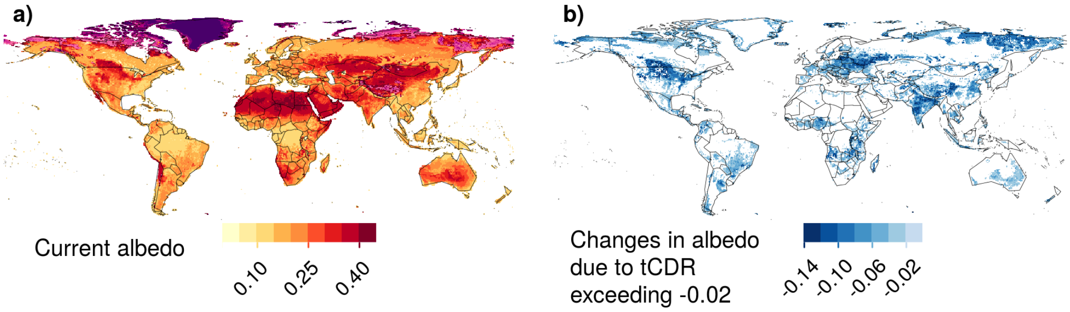

Figure C2: Maps showing the simulated surface albedo in LPJmL for the current state of land-use and natural areas (2005) (a) and areas in which changes in albedo exceed -0.02 if all areas were converted to BP in 2020 (b).

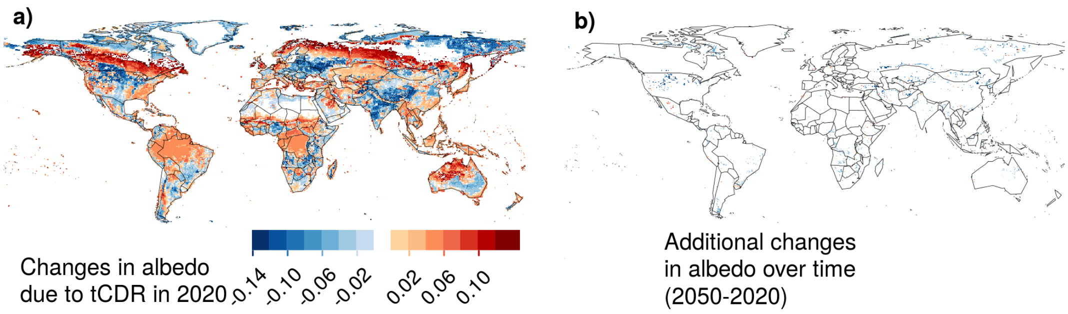

Figure C3: Albedo changes due to complete land conversion to tCDR in 2020 (a) and the additional changes in 2050 due to shifting vegetation over time (b).

tCDR potentials on agricultural land in 2020

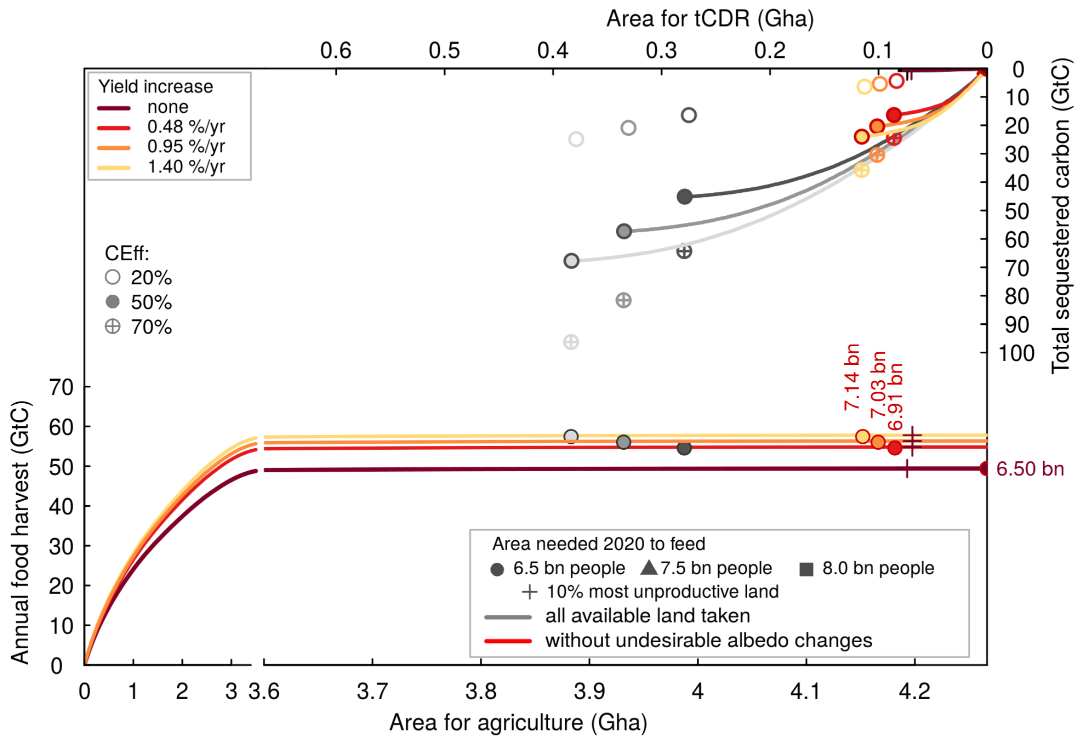

Figure C4: As in Fig. 4.4: tCDR potentials on agricultural land constrained by yield increases and population growth (grey) and albedo (coloured) for the period of 2020–2100.

tCDR potentials on natural land

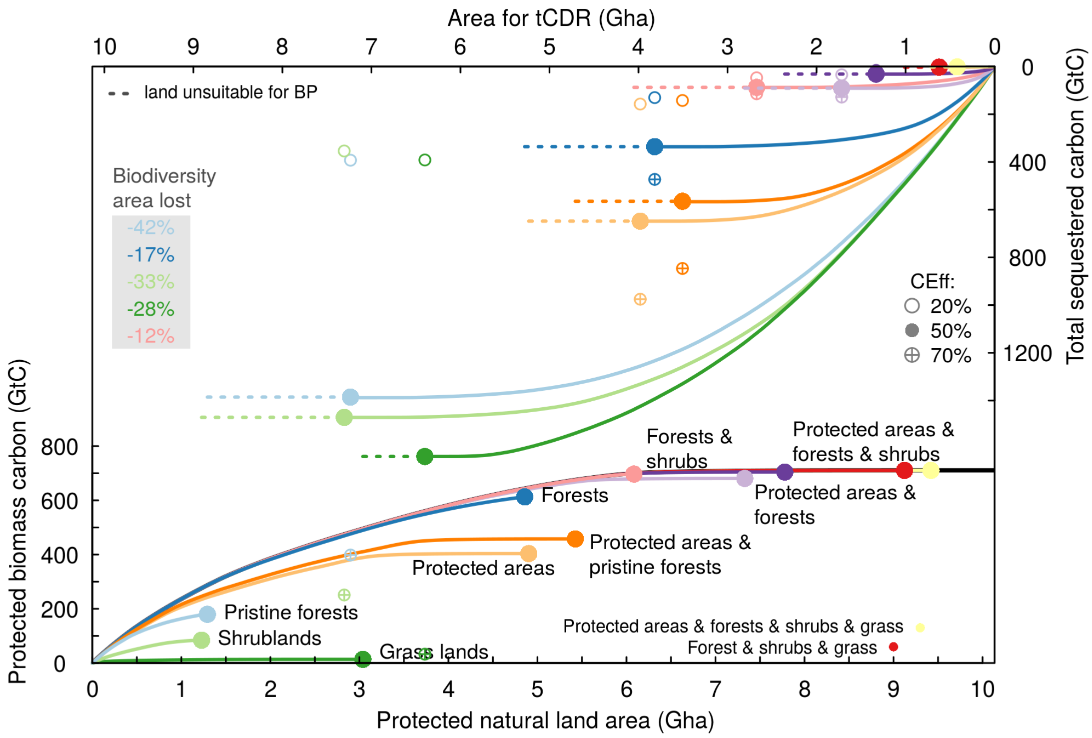

Figure C5: As in Fig 4.6: Vegetation carbon (GtC) of conserved areas and the tCDR potential (GtC) of BPs on unprotected areas depending on different levels of CEff for the period 2020-2100.

Table C.2: Available land for tCDR according to land conservation constraints for biomes and/or protected areas and the resulting tCDR potentials on the remaining, unprotected natural area in dependence to levels of CEff.

Land protected		Vegetation carbon on protected land (GtC)	Area for tCDR (Mha)	tCDR potential (GtC) in dependence to CEff			Protected areas lost (%)
				20%	50%	70%	
2020	Protected areas	404	3981	157	648	975	
Pristine forest		180	7235	393	1385	2047	-42
	+Protected areas	458	3506	142	565	846	
All forests		613	3818	130	336	473	-18
	+Protected areas	681	1717	35	91	128	
Forests + shrub land		607	2673	47	87	114	-12
	+Protected areas	704	1331	16	32	42	
Forest + shrub land + grass land		710	622	2	3	3	-2
	+Protected areas	711	421	1	2	2	
Shrub lands		84	7306	354	1470	2215	-34
Grass lands		14	6400	392	1634	2463	-29
2050	Protected areas	404	4041	56	404	636	
Pristine forest		180	7303	201	879	1331	-43
	+Protected areas	458	3567	55	354	552	
All forests		633	3672	80	191	265	-16
	+Protected areas	690	1673	20	49	68	
Forests + shrub land		702	2563	34	56	71	-11
	+Protected areas	707	1295	12	20	26	
Forest + shrub land + grass land		710	654	1	2	2	-2
	+Protected areas	450	486	1	1	1	
Shrub lands		69	7410	148	936	1461	-33
Grass lands		9	6610	162	1016	1586	-29

D Supplementary analyses conducted during this thesis

The here presented supplementary information was conducted during the work on this thesis. Parts of this section, like the more detailed description of the dynamic global vegetation model LPJmL, deepen the knowledge on the methods used in the presented research. Other parts contributed to the work of other researchers or science outreach activities.

D.1 The transformation of RCP land-use data to LPJmL input data

The representative concentration pathways (RCPs) describe four climate projections reaching different levels of radiative forcing by 2100 and were the basis for the fifth coupled model intercomparison project (CMIP5) and IPCC AR5. The corresponding three land-use change gridded data sets for crop and pasture land as well as bioenergy have been made available for the modelling community. So far, a translation to LPJmL's crop types was missing. In view of a possible use of these scenarios for this thesis I created a script-based algorithm to transform the provided three fractional types to the 16 rainfed and irrigated types used in LPJmL.

The underlying process is rather simple: the total crop extent in LPJmL (year 2005, as described in (Fader et al., 2010)) was up- or downscaled to fit the RCP's given fraction while its 13 crop shares were kept constant. Due to the lack of a detailed documentation, different input data files are now available regarding the irrigated shares in each grid cell: either all expansion takes place without irrigation or 2005's irrigated extent is expanded proportionally. The same procedure was applied for pastures.

However, while crop and pasture land were harmonized (i.e. their sum never exceeds 100% of one grid cell) bioenergy shares were not considered in this process. This means, that it is neither obvious whether bioenergy fractions should be seen as shares of existing crop land nor if they constitute additional shares. Reviewing literature (and contacting the IAM groups responsible for each RCP - no response yet) we preliminary conclude that bioenergy fractions are indeed a share of the given crop land. However, in RCP2.6 for example, ca. 140 Mha out of 440 Mha dedicated bioenergy area do not fit into first, crop land and seconds crop plus pasture land meaning that additional natural land has to be converted. In RCP8.5, gridded data was provided not in terms of fractions but in terms of wood harvest dedicated for bioenergy leaving the user of this data without information of where this wood is actually harvested.

Overall, the new RCP data sets can be used with caution and might need revision once more detailed information about the procedures are available.

The RCP data sets are available on request as:

`_Matti` :based on the updated irrigation patterns as described in Jägermeyr et al., 2015
`100bg` : all dedicated bioenergy area is planted with bioenergy grasses
`100bt` : all dedicated bioenergy area is planted with bioenergy trees
`50bg50bt` : all dedicated bioenergy area is planted with half with bioenergy grasses, half with bioenergy trees

`rainfedexp` : expansion of crop and bioenergy land only rainfed
`irrigexp` : expansion of crop land with irrigated shares (proportionally to 2005's state) and bioenergy rainfed
`irrigbio` : expansion of crop land with irrigated shares (proportionally to 2005's state) and irrigation of bioenergy to proportional shares
`irrigbiomax` : as irrigexp but with fully irrigated bioenergy

These data sets have been used for this thesis, the published paper of Boit et al., 2016 and the manuscripts of Ostberg et al., and Heck et al. (both 2016).

D.2 Synthesis paper on the interaction of land-use and climate

Based on my previous publications (Brovkin et al., 2013; Boysen et al., 2014), I was approached to contribute to the opinion paper named "Grand Challenges in Understanding the Interplay of Climate and Land Changes" submitted by Shuguang Liu (U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS)

Center) to “Earth Interactions” on 11 March, 2016. The chapter deals with the “Overall and Specific Roles of LCLUC (’land cover and land use changes’) on Climate”. DOI: http://dx.doi.org/10.1175/EI-D-16-0012.1.

D.3 Contribution to the Klimawiki of the German Bildungsserver

This study has been financed by public funds and therefore a responsibility and duty arises to inform the public about the research done in the SPP 1689. In that course, I wrote an entry for the Bildungswiki “Klimawande” on tCDR via Afforestation (“Kohlendioxidentzug durch Aufforstung”) which can be found at `http://klimawiki.org` (Deutscher Bildungsserver et al., 2016, accessed 20 March, 2016).

D.4 The dynamic global vegetation model LPJmL — important processes used in this study

This section gives a more detailed description to the model LPJmL which has been the basis to this study. While Section 1.7 provides an overview over the main components of the model, which are presented in more detail in every result chapter, this section gives a deeper insight on the basic simulation processes such as the plant physiology and competition, the carbon cycle and input data.

Natural vegetation distribution

LPJmL simulates the distribution of natural vegetation plant types within each 0.5 times 0.5 degree grid cell dynamically following the competition for light, space and water (Sitch et al., 2003). The underlying model version does not yet include nutrient limitation, but water and heat stress, fires (Thonicke et al., 2001). Also, inadequate growth conditions and plant densities constitute challenges for each plant stand (mortality). The establishment of new vegetation depends the existing vegetation and, again, on climatic conditions.

Since the model cannot simulate individual species or even plants due to high computational costs, plant functional types (PFTs) group main functional characteristics across all species into nine idealised average plant types such as tropical broadleaf evergreen trees, boreal needleleaf trees or shrubs. These are then again grouped into averaged individuals in each grid cell. Main parameters and processes include specific leaf area (SLA), fire tolerance, tree architecture (e.g. crown area, height, stem diatmeter), carbon allocation and water stress behaviour.

Each PFT is therefore described by a different set of parameters and processes regarding phenology and carbon allocation. Photosynthesis is the main driver of plant physiological processes. Through small openings on the leaf surface (stomata), CO_2 is taken up and converted to sugar molecules (carbon) using light energy (photosynthetic active radiation, PAR) while water is lost through transpiration. During night time CO_2 is respirated. Under rising CO_2 concentrations the number of stomata rises and plants can assimilate more carbon. These stomata are closed if the ambient air temperature is too high or under water stress to prevent additional water loss.

Dead matter is transferred to a litter carbon pool (with a turnover rate) where microbes decompose this biomass (heterotrophic respiration) and carbon is partly emitted to the atmosphere. The activity of these microbes is governed by soil temperature and water content (e.g. high temperatures lead to higher respiration). The overall biomass carbon allocation in the storage organs of fine roots, leaves, sapwood, heartwood depends on the available radiation, leaf temperature, water supply and respiration (net primary production = carbon assimilation minus respiration). Soil carbon content (slow and fast soil pools, six layers) depends on litter production and turnover rates. Carbon allocation (vegetation, litter and soil) in the model is calculated on an annual basis first for each PFT separately and then averaged over all PFTs.

Precipitation provides the water needed for the terrestrial plant growth. Plants can access water directly by interception through leaves or by extracting percolated soil water through their roots. Snowmelt and permafrost thawing can provide additional water which can however be made inaccessible for plants through surface evaporation, surface runoff or subsurface water flows (Gerten et al., 2004).

Simulations start in 1901 with a 5000 years spin-up to reach equilibrium of soil carbon and vegetation patterns (Schaphoff et al., 2013). Another spin-up period of 390 years allows for the adaptation to land-use. During each spin-up time, the first 30 years of the climate forcing (1901-1931) are randomly cycled.

Climate input

The climate forcing in LPJmL consists of data sets for monthly temperature, precipitation, cloudiness and number of wet days (Gerten et al., 2004). For the historical period, these data sets are provided by the Climatic Research Unit (CRU TS version 3.10, Harris et al., 2014) for temperatures and by the Global Precipitation Climatology Centre (GPCC Full Data Reanalysis Version 5.0, Schamm et al., 2014). Information on soil properties and lakes, reservoirs and river geography and annual atmospheric CO_2 concentrations are provided as well.

For the use future climate projections, climate model data (temperature, precipitation and cloud cover) had to be adapted. Grid sized were rescaled to the 0.5 x 0.5 resolution using the bilinear interpolation. At each grid point, these data sets were then corrected for systematic errors in mean and variance applying a quantile mapping approach based for continuous time series similar to the method described in Watanabe et al. (2012). This method preserves trends (changes in mean and variance) by applying an offset factor derived from comparing model results against observations (CRU TS 3.10 and GPCC version 6 for CMIP3 models used in Chapter 2-4 and CRU TS 3.21 and GPCC version 6 for CMIP5 models used in Chapter 5) while higher moments or autocorrelations remain unchanged.

D.4.1 Managed land

LPJmL simulates yields of 13 different crop functional types (CFTs), pastures and bioenergy functional types (BFTs, see below). The CFTs were grouped to represent 12 main crop types (e.g. wheat, maize, rice), one pasture type representing nutritious crops (e.g. citrous fruits) and fibre (e.g. cotton) and another type representing pastures (Bondeau et al., 2007). On a daily time step, carbon is allocated in leaves, stems, roots and storage organs (e.g. grains for cereals) in dependence on heat and water stress.

The distribution of irrigated and rainfed crops and pastures from 1700 to 2005 was derived by Bondeau et al. (2007) and updated by Fader et al. (2010) based on data sets provided by Portmann et al. (2010), Monfreda et al. (2008), and Ramankutty et al. (2008).

Management options include the calibration of yields by adapting plant specific parameters and irrigation. Irrigation patterns depend on the distribution and irrigation system (e.g. sprinkler, drip and surface) given by Jägermeyr et al. (2015) whereby water can be withdrawn sustainably (limitation depending water reservoirs and river systems) or unlimited (potential irrigation, Gerten et al., 2004). Crop specific harvest parameters include the harvest index (HI), the maximum leaf area index (LAI_{max}) and 'Alpha a' (α_a) which are proportionally coupled to each other. HI defines the optimum proportion of the storage organ which is harvested; the remainder of the plant (roots, straw and stubble) are transferred to the litter pool and respired within one year. $\mathrm{LAI}_{\mathrm{max}}$ describes the maximum leaf area size that could be reached under optimal growing conditions and thus, can be referred to as the general plant performance. α_{a} controls the photosynthetic activity at the leaf level (controlling the carbon assimilation of a stand). Based on annual national yield statistics of the FAO, these model parameters are calibrated to meet observations.

Bioenergy plantations

Two bioenergy functional types group herbaceous (grasses, BG) and woody (trees, BT) bioenergy species. As described in the method sections of the main studies, they were characterised to represent the main features of, for BT, temperate willows and poplars, tropical *Eucalyptus* and for BG, Switchgrass and *Miscanthus* (Beringer et al., 2011). Heck et al. (2016) provided a comparison of field experiment results with simulated bioenergy yields by choosing the same location and providing irrigation if required. The model represents bioenergy plants well at a global scale but cannot represent specifically managed plantations (different soils, pre-grown saplings, intensive care).

Bioenergy trees grow for eight years when they are cut down near the ground (65% of sapwood and 90% or heart wood are removed). This procedure allows for a faster regrowth due to the intact root system. After 40 years, the whole plantation is removed and newly established with saplings raised on the field (note, most field studies grow saplings in greenhouses before transferring them to the field). These time intervals were found to be reasonable in comparison with literature (Lemus and Lal, 2005; Langholtz et al., 2007; Heller et al., 2003) and in sensitivity analyses conducted with LPJmL.

Bioenergy grasses are harvested as soon as 400 g m^{-2} are reached or, in low productivity areas, if leaf mass has reduced to 75% of its maximum value at the end of the growing season. The harvest fraction is set to 85% following Johnson et al. (2012) and Ashworth et al. (2013) and shown to be an optimal value in our model (e.g. an increased harvest fraction would reduce biomass yields).

If bioenergy replaces natural vegetation in our model, these natural wood can be harvested and stored as a one-time event. For this, two thirds of the sapwood and all heartwood is harvested and not transferred to the litter pool.

Bibliography

Acaroğlu, M. and A. Şemi Aksoy (2005). „The Cultivation and Energy Balance of Miscanthusgiganteus Production in Turkey“. *Biomass and Bioenergy*, **29**, no. 1, pp. 42–48.

Adegbidi, H. G., R. D. Briggs, T. A. Volk, E. H. White, and L. P. Abrahamson (2003). „Effect of Organic Amendments and Slow-Release Nitrogen Fertilizer on Willow Biomass Production and Soil Chemical Characteristics“. *Biomass and Bioenergy*, **25**, no. 4, pp. 389–398.

Adler, P. R., M. A. Sanderson, A. A. Boateng, P. J. Weimer, and H.-J. G. Jung (2006). „Biomass Yield and Biofuel Quality of Switchgrass Harvested in Fall or Spring“. *Agronomy Journal*, **98**, no. 6, p. 1518.

Alexandratos, N. and J. Bruinsma (2012). „World Agriculture towards 2030/2050: The 2012 Revision“. **2**.

Anav, A., P. Friedlingstein, M. Kidston, L. Bopp, P. Ciais, P. Cox, C. Jones, M. Jung, R. Myneni, and Z. Zhu (2013). „Evaluating the Land and Ocean Components of the Global Carbon Cycle in the CMIP5 Earth System Models“. *Journal of Climate*, p. 130401082723008.

Aravindhakshan, S. C., F. M. Epplin, and C. M. Taliaferro (2010). „Economics of Switchgrass and Miscanthus Relative to Coal as Feedstock for Generating Electricity“. *Biomass and Bioenergy*, **34**, no. 9, pp. 1375–1383.

Archer, D. and V. Brovkin (2008). „The Millennial Atmospheric Lifetime of Anthropogenic CO 2“. *Climatic Change*, **90**, no. 3, pp. 283–297.

Arnell, N. W., S. Brown, S. N. Gosling, P. Gottschalk, J. Hinkel, et al. (2014). „The Impacts of Climate Change across the Globe: A Multi-Sectoral Assessment“. *Climatic Change*, pp. 1–18.

Arora, V., J. Scinocca, G. Boer, J. Christian, K. Denman, G. Flato, V. Kharin, W. Lee, and W. Merryfield (2011). „Carbon Emission Limits Required to Satisfy Future Representative Concentration Pathways of Greenhouse Gases“. *Geophysical Research Letters*, **38**, no. 5, p. L05805.

Ashworth, A. J., P. D. Keyser, E. D. Holcomb, and C. A. Harper (2013). „Yield and Stand Persistence of Switchgrass as Affected by Cutting Height and Variety“. *Forage and Grazinglands*, **11**, no. 1, Azar, C., K. Lindgren, M. Obersteiner, K. Riahi, D. P. van Vuuren, K. M. G. J. den Elzen, K. Möllersten, and E. D. Larson (2010). „The Feasibility of Low CO2 Concentration Targets and the Role of Bio-Energy with Carbon Capture and Storage (BECCS)“. *Climatic Change*, **100**, no. 1, pp. 195–202.

Bajželj, B., K. S. Richards, J. M. Allwood, P. Smith, J. S. Dennis, E. Curmi, and C. A. Gilligan (2014). „Importance of Food-Demand Management for Climate Mitigation“. *Nature Climate Change*, **4**, no. 10, pp. 924–929.

Barnett, J. (2003). „Security and Climate Change“. *Global Environmental Change*, **13**, no. 1, pp. 7–17.

Barnett, J. and W. N. Adger (2007). „Climate Change, Human Security and Violent Conflict“. *Political Geography.* Climate Change and Conflict **26**, no. 6, pp. 639–655.

Barrett, S., T. M. Lenton, A. Millner, A. Tavoni, S. Carpenter, et al. (2014). „Climate Engineering Reconsidered“. *Nature Climate Change*, **4**, no. 7, pp. 527–529.

Bathiany, S., M. Claussen, V. Brovkin, T. Raddatz, and V. Gayler (2010). „Combined Biogeophysical and Biogeochemical Effects of Large-Scale Forest Cover Changes in the MPI Earth System Model“. *Biogeosciences*, **7**, no. 5, pp. 1383–1399.

Bennett, D. J. and R. C. Jennings (2013). *Successful Agricultural Innovation in Emerging Economies: New Genetic Technologies for Global Food Production.* Cambridge University Press.

Beringer, T., W. Lucht, and S. Schaphoff (2011). „Bioenergy Production Potential of Global Biomass Plantations under Environmental and Agricultural Constraints“. *GCB Bioenergy*, **3**, no. 4, pp. 299–312.

Berthelot, A. and A. Gavaland (2015). „Produire de La Biomasse Avec Des Taillis de Peupliers“. *Informations forêt*, no. 4, 4.

Bertram, C., N. Johnson, G. Luderer, K. Riahi, M. Isaac, and J. Eom (2015). „Carbon Lock-in through Capital Stock Inertia Associated with Weak near-Term Climate Policies“. *Technological Forecasting and Social Change*, **90, Part A**, pp. 62–72.

Binkley, D., R. Senock, S. Bird, and T. G. Cole (2003). „Twenty Years of Stand Development in Pure and Mixed Stands of Eucalyptus Saligna and Nitrogen-Fixing Facaltaria Moluccana“. *Forest Ecology and Management*, **182**, no. 1–3, pp. 93–102.

Black, R., D. Kniveton, and K. Schmidt-Verkerk (2013). „Migration and Climate Change: Toward an Integrated Assessment of Sensitivity“. *Disentangling Migration and Climate Change.* Ed. by T. Faist and J. Schade. Springer Netherlands, pp. 29–53.

Blair, N., A. Leu, E. Muñoz, J. Olsen, E. Kwong, and D. D. Marais (1985). „Carbon Isotopic Fractionation in Heterotrophic Microbial Metabolism.“ *Applied and Environmental Microbiology*, **50**, no. 4, pp. 996–1001.

Boit, A., B. Sakschewski, L. Boysen, A. Cano-Crespo, J. Clement, et al. (2016). „Large-Scale Impact of Climate Change versus Land-Use Change on Future Biome Shifts in Latin America“. *Global Change Biology*, n/a–n/a.

Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, et al. (2007). „Modelling the Role of Agriculture for the 20th Century Global Terrestrial Carbon Balance“. *Global Change Biology*, **13**, no. 3, pp. 679–706.

Boysen, L. R., V. Brovkin, V. K. Arora, P. Cadule, N. de Noblet-Ducoudré, E. Kato, J. Pongratz, and V. Gayler (2014). „Global and Regional Effects of Land-Use Change on Climate in 21st Century Simulations with Interactive Carbon Cycle“. *Earth Syst. Dynam. Discuss.* **5**, no. 1, pp. 443–472.

Bronstein, M. (2010). „Readily Deployable Approaches To Geoengineering: Cool Materials And Aggressive Reforestation“. *Sustainable Development Law & Policy*, **10**, no. 2.

Brosse, N., A. Dufour, X. Meng, Q. Sun, and A. Ragauskas (2012). „Miscanthus: A Fast-Growing Crop for Biofuels and Chemicals Production“. *Biofuels, Bioproducts and Biorefining*, **6**, no. 5, pp. 580–598.

Brovkin, V., L. Boysen, V. K. Arora, J. P. Boisier, P. Cadule, et al. (2013). „Effect of Anthropogenic Land-Use and Land-Cover Changes on Climate and Land Carbon Storage in CMIP5 Projections for the Twenty-First Century“. *Journal of Climate*, **26**, no. 18, pp. 6859–6881.

Caiazzo, F., R. Malina, M. D. Staples, P. J. Wolfe, S. H. L. Yim, and S. R. H. Barrett (2014). „Quantifying the Climate Impacts of Albedo Changes Due to Biofuel Production: A Comparison with Biogeochemical Effects“. *Environmental Research Letters*, **9**, no. 2, p. 024015.

Caldeira, K., G. Bala, and L. Cao (2013). „The Science of Geoengineering“. *Annual Review of Earth and Planetary Sciences*, **41**, no. 1, pp. 231–256.

Cannell, M. G. R. (1980). „Productivity of Closely-Spaced Young Poplar on Agricultural Soils in Britain“. *Forestry*, **53**, no. 1, pp. 1–21.

Cannell, M. G. R. (2003). „Carbon Sequestration and Biomass Energy Offset: Theoretical, Potential and Achievable Capacities Globally, in Europe and the UK“. *Biomass and Bioenergy*, **24**, no. 2, pp. 97–116.

Ceballos, G., P. R. Ehrlich, A. D. Barnosky, A. Garc´a, R. M. Pringle, and T. M. Palmer (2015). „Accelerated Modern Human–induced Species Losses: Entering the Sixth Mass Extinction“. *Science Advances*, **1**, no. 5, e1400253.

Chan, K. M. A., P. Balvanera, K. Benessaiah, M. Chapman, S. D´az, et al. (2016). „Opinion: Why Protect Nature? Rethinking Values and the Environment“. *Proceedings of the National Academy of Sciences*, **113**, no. 6, pp. 1462–1465.

Christian, D. G., A. B. Riche, and N. E. Yates (2008). „Growth, Yield and Mineral Content of Miscanthus × Giganteus Grown as a Biofuel for 14 Successive Harvests". *Industrial Crops and Products*, **28**, no. 3, pp. 320–327.

Clifton-Brown, J. C., J. Breuer, and M. B. Jones (2007). „Carbon Mitigation by the Energy Crop, Miscanthus". *Global Change Biology*, **13**, no. 11, pp. 2296–2307.

Clifton-Brown, J. C., P. F. Stampfl, and M. B. Jones (2004). „Miscanthus Biomass Production for Energy in Europe and Its Potential Contribution to Decreasing Fossil Fuel Carbon Emissions". *Global Change Biology*, **10**, no. 4, pp. 509–518.

Corner, A. and N. Pidgeon (2014). „Geoengineering, Climate Change Scepticism and the 'Moral Hazard' Argument: An Experimental Study of UK Public Perceptions". *Phil. Trans. R. Soc. A*, **372**, no. 2031, p. 20140063.

Coumou, D., J. Lehmann, and J. Beckmann (2015). „The Weakening Summer Circulation in the Northern Hemisphere Mid-Latitudes". *Science*, **348**, no. 6232, pp. 324–327.

Cramer, W., D. W. Kicklighter, A. Bondeau, B. M. Iii, G. Churkina, B. Nemry, A. Ruimy, A. L. Schloss, and T. P. O. T. P. N. M. Intercomparison (1999). „Comparing Global Models of Terrestrial Net Primary Productivity (NPP): Overview and Key Results". *Global Change Biology*, **5**, no. S1, pp. 1–15.

Cramer, W., A. Bondeau, F. I. Woodward, I. C. Prentice, R. A. Betts, et al. (2001). „Global Response of Terrestrial Ecosystem Structure and Function to CO2 and Climate Change: Results from Six Dynamic Global Vegetation Models". *Global Change Biology*, **7**, no. 4, pp. 357–373.

Crombie, K., O. Mašek, A. Cross, and S. Sohi (2014). „Biochar – Synergies and Trade-Offs between Soil Enhancing Properties and C Sequestration Potential". *GCB Bioenergy*.

Crutzen, P. J. (2006a). „Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" *Climatic Change*, **77**, no. 3-4, pp. 211–220.

– (2006b). „The "Anthropocene"". *Earth System Science in the Anthropocene*. Ed. by P. D. E. Ehlers and D. T. Krafft. Springer Berlin Heidelberg, pp. 13–18.

Danalatos, N. G., S. V. Archontoulis, and I. Mitsios (2007). „Potential Growth and Biomass Productivity of Miscanthus×giganteus as Affected by Plant Density and N-Fertilization in Central Greece". *Biomass and Bioenergy*, **31**, no. 2–3, pp. 145–152.

Davin, E. L., S. I. Seneviratne, P. Ciais, A. Olioso, and T. Wang (2014). „Preferential Cooling of Hot Extremes from Cropland Albedo Management". *Proceedings of the National Academy of Sciences*, **111**, no. 27, pp. 9757–9761.

Davin, E. and N. de Noblet-Ducoudré (2010). „Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes". *Journal of Climate*, **23**, no. 1, pp. 97–112.

Davin, E., N. de Noblet-Ducoudré, and P. Friedlingstein (2007). „Impact of Land Cover Change on Surface Climate: Relevance of the Radiative Forcing Concept". *Geophysical research letters*, **34**, no. 13, p. L13702.

Davis, M. P., M. B. David, T. B. Voigt, and C. A. Mitchell (2014). „Effect of Nitrogen Addition on Miscanthus × Giganteus Yield, Nitrogen Losses, and Soil Organic Matter across Five Sites". *GCB Bioenergy*, n/a–n/a.

DeLucia, E. (2015). „How Biofuels Can Cool Our Climate and Strengthen Our Ecosystems". *Eos*, **96**.

Demo, M. (2013). „Biomass Production Potential of Different Willow Varieties (Salix Spp.) Grown in Soil-Climatic Conditions of South-Western Slovakia." *Wood Research*, **58**, no. 4, pp. 651–661.

Deutsche Forschungsgesellschaft (2013). *CE-Land - SPP Climate Engineering*. `http://www.spp-climate-engineering.de/CE-LAND.html`.

Deutscher Bildungsserver, Climate Service Center, and Hamburger Bildungsserver (2016). *Kohlendioxidentzug Durch Aufforstung – Klimawandel*. `http://klimawiki.org/klimawandel/index.php/Kohlendioxidentzug_durch_Aufforstung`.

Di Virgilio, N., A. Monti, and G. Venturi (2007). „Spatial Variability of Switchgrass (Panicum Virgatum L.) Yield as Related to Soil Parameters in a Small Field". *Field Crops Research*, **101**, no. 2, pp. 232–239.

Diffenbaugh, N. S., D. L. Swain, and D. Touma (2015). „Anthropogenic Warming Has Increased Drought Risk in California". *Proceedings of the National Academy of Sciences*, **112**, no. 13, pp. 3931–3936.

Dlugokencky, E. and P. Tans (2016). *ESRL Global Monitoring Division - Global Greenhouse Gas Reference Network*. `http://www.esrl.noaa.gov/gmd/ccgg/trends/`.

Dornburg, V., D. van Vuuren, G. van de Ven, H. Langeveld, M. Meeusen, et al. (2010). „Bioenergy Revisited: Key Factors in Global Potentials of Bioenergy". *Energy & Environmental Science*, **3**, no. 3, pp. 258–267.

Dowell, R. C., D. Gibbins, J. L. Rhoads, and S. G. Pallardy (2009). „Biomass Production Physiology and Soil Carbon Dynamics in Short-Rotation-Grown Populus Deltoides and P. Deltoides × P. Nigra Hybrids". *Forest Ecology and Management*, **257**, no. 1, pp. 134–142.

Edenhofer, O. (2015). „King Coal and the Queen of Subsidies". *Science*, **349**, no. 6254, pp. 1286–1287.

Edenhofer, O. and Intergovernmental Panel on Climate Change, eds. (2014). *Climate Change 2014: Mitigation of Climate Change ; Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* New York, NY: Cambridge Univ. Press.

Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, S. Kadner, et al. (2011). *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Edmonds, J., P. Luckow, K. Calvin, M. Wise, J. Dooley, P. Kyle, S. H. Kim, P. Patel, and L. Clarke (2013). „Can Radiative Forcing Be Limited to 2.6 Wm-2 without Negative Emissions from Bioenergy AND CO2 Capture and Storage?“ *Climatic Change*, **118**, no. 1, pp. 29–43.

Ellis, E. C., K. Klein Goldewijk, S. Siebert, D. Lightman, and N. Ramankutty (2010). „Anthropogenic Transformation of the Biomes, 1700 to 2000“. *Global Ecology and Biogeography*, **19**, no. 5, pp. 589–606.

Enzing, C., M. Ploeg, M. Barbosa, L. Sijtsma, M. Vigani, C. Parisi, E. Rodr´guez Cerezo, and Institute for Prospective Technological Studies (2014). *Microalgae-Based Products for the Food and Feed Sector an Outlook for Europe.* Luxembourg: Publications Office.

Erb, K.-H., T. Fetzel, C. Plutzar, T. Kastner, C. Lauk, A. Mayer, M. Niedertscheider, C. Körner, and H. Haberl (2016). „Biomass Turnover Time in Terrestrial Ecosystems Halved by Land Use“. *Nature Geoscience*, **9**, no. 9, pp. 674–678.

Erb, K.-H., H. Haberl, and C. Plutzar (2012). „Dependency of Global Primary Bioenergy Crop Potentials in 2050 on Food Systems, Yields, Biodiversity Conservation and Political Stability“. *Energy Policy*, **47**, pp. 260–269.

Evans, L. T. (1998). *Feeding the Ten Billion: Plants and Population Growth.* Cambridge University Press.

Fader, M., S. Rost, C. Müller, A. Bondeau, and D. Gerten (2010). „Virtual Water Content of Temperate Cereals and Maize: Present and Potential Future Patterns“. *Journal of Hydrology.* Green-Blue Water Initiative (GBI) **384**, no. 3–4, pp. 218–231.

FAO (2015). *World Fertilizer Trends and Outlook to 2018.* Rome: Food & Agriculture Organization of United Nations.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, et al. (2011). „Solutions for a Cultivated Planet“. *Nature*, **478**, no. 7369, pp. 337–342.

Forkel, M., N. Carvalhais, S. Schaphoff, W. v. Bloh, M. Migliavacca, M. Thurner, and K. Thonicke (2014). „Identifying Environmental Controls on Vegetation Greenness Phenology through Model–data Integration“. *Biogeosciences*, **11**, no. 23, pp. 7025–7050.

Francis, G., R. Edinger, and K. Becker (2005). „A Concept for Simultaneous Wasteland Reclamation, Fuel Production, and Socio-Economic Development in Degraded Areas in India: Need, Potential and Perspectives of Jatropha Plantations“. *Natural Resources Forum*, **29**, no. 1, pp. 12–24.

Friend, A. D., W. Lucht, T. T. Rademacher, R. Keribin, R. Betts, et al. (2014). „Carbon Residence Time Dominates Uncertainty in Terrestrial Vegetation Responses to Future Climate and Atmospheric CO2“. *Proceedings of the National Academy of Sciences*, **111**, no. 9, pp. 3280–3285.

Fuss, S., J. G. Canadell, G. P. Peters, M. Tavoni, R. M. Andrew, et al. (2014). „Betting on Negative Emissions“. *Nature Climate Change*, **4**, no. 10, pp. 850–853.

Gan, T. Y., M. Ito, S. Hülsmann, X. Qin, X. X. Lu, S. Y. Liong, P. Rutschman, M. Disse, and H. Koivusalo (2016). „Possible Climate Change/Variability and Human Impacts, Vulnerability of Drought-Prone Regions, Water Resources and Capacity Building for Africa“. *Hydrological Sciences Journal*, **61**, no. 7, pp. 1209–1226.

Gerten, D., H. Hoff, J. Rockström, J. Jägermeyr, M. Kummu, and A. V. Pastor (2013). „Towards a Revised Planetary Boundary for Consumptive Freshwater Use: Role of Environmental Flow Requirements“. *Current Opinion in Environmental Sustainability*, **5**, no. 6, pp. 551–558.

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch (2004). „Terrestrial Vegetation and Water Balance—hydrological Evaluation of a Dynamic Global Vegetation Model“. *Journal of Hydrology*, **286**, no. 1–4, pp. 249–270.

Gilbert, A. and B. K. Sovacool (2015). „Emissions Accounting for Biomass Energy with CCS“. *Nature Climate Change*, **5**, no. 6, pp. 495–496.

Gillett, N. P., V. K. Arora, D. Matthews, and M. R. Allen (2013). „Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations*“. *Journal of Climate*, **26**, no. 18, pp. 6844–6858.

Godfray, H. C. J., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin (2010). „Food Security: The Challenge of Feeding 9 Billion People“. *Science*, **327**, no. 5967, pp. 812–818.

Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010). „GLOBAL SURFACE TEMPERATURE CHANGE“. *Reviews of Geophysics*, **48**, no. 4.

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, et al. (2013). „High-Resolution Global Maps of 21st-Century Forest Cover Change“. *Science*, **342**, no. 6160, pp. 850–853.

Harris, I., P. Jones, T. Osborn, and D. Lister (2014). „Updated High-Resolution Grids of Monthly Climatic Observations – the CRU TS3.10 Dataset“. *International Journal of Climatology*, **34**, no. 3, pp. 623–642.

Heaton, E. A., F. G. Dohleman, and S. P. Long (2008). „Meeting US Biofuel Goals with Less Land: The Potential of Miscanthus“. *Global Change Biology*, **14**, no. 9, pp. 2000–2014.

Heck, V., D. Gerten, W. Lucht, and L. R. Boysen (2016). „Is Extensive Terrestrial Carbon Dioxide Removal a ‘Green’ Form of Geoengineering? A Global Modelling Study“. *Global and Planetary Change*, **137**, pp. 123–130.

Heinke, J., S. Ostberg, S. Schaphoff, K. Frieler, C. Müller, D. Gerten, M. Meinshausen, and W. Lucht (2013). „A New Climate Dataset for Systematic Assessments of Climate Change Impacts as a Function of Global Warming“. *Geoscientific Model Development*, **6**, no. 5, pp. 1689–1703.

Heller, M. C., G. A. Keoleian, and T. A. Volk (2003). „Life Cycle Assessment of a Willow Bioenergy Cropping System“. *Biomass and Bioenergy*, **25**, no. 2, pp. 147–165.

Herring, S., M. P. Hoerling, J. P. Kossin, T. C. Peterson, and P. A. Stott (2015). „2015: Explaining Extreme Events of 2014 from a Climate Perspective“. **96**, no. 12, SI–SI72.

Hertel, T. W. and U. L. C. Baldos (2016). „Global Change and the Food System in 2050“. *Global Change and the Challenges of Sustainably Feeding a Growing Planet.* Springer International Publishing, pp. 141–160.

Himken, M., J. Lammel, D. Neukirchen, U. Czypionka-Krause, and H.-W. Olfs (1997). „Cultivation of Miscanthus under West European Conditions: Seasonal Changes in Dry Matter Production, Nutrient Uptake and Remobilization“. *Plant and Soil*, **189**, no. 1, pp. 117–126.

Hofmann-Schielle, C., A. Jug, F. Makeschin, and K. E. Rehfuess (1999). „Short-Rotation Plantations of Balsam Poplars, Aspen and Willows on Former Arable Land in the Federal Republic of Germany. I. Site–growth Relationships“. *Forest Ecology and Management*, **121**, no. 1–2, pp. 41–55.

Horton, D. E., N. C. Johnson, D. Singh, D. L. Swain, B. Rajaratnam, and N. S. Diffenbaugh (2015). „Contribution of Changes in Atmospheric Circulation Patterns to Extreme Temperature Trends“. *Nature*, **522**, no. 7557, pp. 465–469.

Horton, R., K. L. Bristow, G. J. Kluitenberg, and T. J. Sauer (1996). „Crop Residue Effects on Surface Radiation and Energy Balance — Review“. *Theoretical and Applied Climatology*, **54**, no. 1-2, pp. 27–37.

House, J. I., I. Colin Prentice, and C. Le Quéré (2002). „Maximum Impacts of Future Reforestation or Deforestation on Atmospheric CO2“. *Global Change Biology*, **8**, no. 11, pp. 1047–1052.

Humpenöder, F., A. Popp, J. P. Dietrich, D. Klein, H. Lotze-Campen, M. Bonsch, B. L. Bodirsky, I. Weindl, M. Stevanovic, and C. Müller (2014). „Investigating Afforestation and Bioenergy CCS as Climate Change Mitigation Strategies“. *Environmental Research Letters*, **9**, no. 6, p. 064029.

Humpenöder, F., A. Popp, M. Stevanovic, C. Müller, B. L. Bodirsky, et al. (2015). „Land-Use and Carbon Cycle Responses to Moderate Climate Change: Implications for Land-Based Mitigation?“ *Environmental Science & Technology*, **49**, no. 11, pp. 6731–6739.

Hunter, I. (2001). „Above Ground Biomass and Nutrient Uptake of Three Tree Species (Eucalyptus Camaldulensis, Eucalyptus Grandis and Dalbergia Sissoo) as Affected by Irrigation and Fertiliser, at 3 Years of Age, in Southern India“. *Forest Ecology and Management*, **144**, no. 1–3, pp. 189–200.

Hurtt, G., L. Chini, S. Frolking, R. Betts, J. Feddema, G. Fischer, J. Fisk, K. Hibbard, R. Houghton, A. Janetos, et al. (2011). „Harmonization of Land-Use Scenarios for the Period 1500–2100: 600 Years of Global Gridded Annual Land-Use Transitions, Wood Harvest, and Resulting Secondary Lands“. *Climatic Change*, pp. 1–45.

Intergovernmental Panel on Climate Change (2014). „Agriculture, Forestry and Other Land Use (AFOLU)“. *Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

IUCN and UNEP-WCMC (2015). *The World Database on Protected Areas (WDPA).* http://www.protectedplanet.net/.

Jägermeyr, J., D. Gerten, J. Heinke, S. Schaphoff, M. Kummu, and W. Lucht (2015). „Water Savings Potentials of Irrigation Systems: Global Simulation of Processes and Linkages“. *Hydrol. Earth Syst. Sci.* **19**, no. 7, pp. 3073–3091.

Jamieson, D. (2013). „Some Whats, Whys and Worries of Geoengineering“. *Climatic Change*, **121**, no. 3, pp. 527–537.

Jantz, P., S. Goetz, and N. Laporte (2014). „Carbon Stock Corridors to Mitigate Climate Change and Promote Biodiversity in the Tropics“. *Nature Climate Change*, **4**, no. 2, pp. 138–142.

Jeffery, L., C. Fyson, R. Alexander, J. Gütschow, M. Rocha, et al. (2015). *Climate Pledges Will Bring 2.7°C of Warming, Potential for More Action - Climate Action Tracker.* http://climateactiontracker.org/news/253/Climate-pledges-will-bring-2.7C-of-warming-potential-for-more-action.html.

Johnson, P. C., C. L. Clementson, S. K. Mathanker, T. E. Grift, and A. C. Hansen (2012). „Cutting Energy Characteristics of Miscanthus x Giganteus Stems with Varying Oblique Angle and Cutting Speed“. *Biosystems Engineering*, **112**, no. 1, pp. 42–48.

Jørgensen, U., J. Mortensen, J. B. Kjeldsen, and K.-u. Schwarz* (2003). „Establishment, Development and Yield Quality of Fifteen Miscanthus Genotypes over Three Years in Denmark“. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, **53**, no. 4, pp. 190–199.

Kahle, P., S. Beuch, B. Boelcke, P. Leinweber, and H.-R. Schulten (2001). „Cropping of Miscanthus in Central Europe: Biomass Production and Influence on Nutrients and Soil Organic Matter“. *European Journal of Agronomy*, **15**, no. 3, pp. 171–184.

Karp, A. and I. Shield (2008). „Bioenergy from Plants and the Sustainable Yield Challenge“. *New Phytologist*, **179**, no. 1, pp. 15–32.

Kato, E. and Y. Yamagata (2014). „BECCS Capability of Dedicated Bioenergy Crops under a Future Land-Use Scenario Targeting Net Negative Carbon Emissions“. *Earth's Future*, 2014EF000249.

Keeling, C. D. (1960). „The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere“. *Tellus*.

Keeling, C. D., S. C. Piper, R. B. Bacastow, M. Wahlen, T. P. Whorf, M. Heimann, and H. A. Meijer (2005). „Atmospheric CO2 and 13CO2 Exchange with the Terrestrial Biosphere and Oceans from 1978 to 2000: Observations and Carbon Cycle Implications“. *A History of Atmospheric CO2 and Its Effects on Plants, Animals, and Ecosystems*. Ed. by I. T. Baldwin, M. M. Caldwell, G. Heldmaier, R. B. Jackson, O. L. Lange, et al. Ecological Studies 177. Springer New York, pp. 83–113.

Keeling, C. D. and T. P. Whorf (2005). „Atmospheric CO2 Records from Sites in the SIO Air Sampling Network“. *Trends: a compendium of data on global change*, **2009**.

Keenan, R. J., G. A. Reams, F. Achard, J. V. de Freitas, A. Grainger, and E. Lindquist (2015). „Dynamics of Global Forest Area: Results from the FAO Global Forest Resources Assessment 2015“. *Forest Ecology and Management*. Changes in Global Forest Resources from 1990 to 2015 **352**, pp. 9–20.

Keith, D. (2013). *A Case for Climate Engineering*. MIT Press.

Keller, D. P., E. Y. Feng, and A. Oschlies (2014). „Potential Climate Engineering Effectiveness and Side Effects during a High Carbon Dioxide-Emission Scenario“. *Nature Communications*, **5**.

Kering, M. K., T. J. Butler, J. T. Biermacher, and J. A. Guretzky (2011). „Biomass Yield and Nutrient Removal Rates of Perennial Grasses under Nitrogen Fertilization“. *BioEnergy Research*, **5**, no. 1, pp. 61–70.

Kier, G., H. Kreft, T. M. Lee, W. Jetz, P. L. Ibisch, C. Nowicki, J. Mutke, and W. Barthlott (2009). „A Global Assessment of Endemism and Species Richness across Island and Mainland Regions“. *Proceedings of the National Academy of Sciences*, **106**, no. 23, pp. 9322–9327.

Klein, D., F. Humpenöder, N. Bauer, J. P. Dietrich, A. Popp, B. L. Bodirsky, M. Bonsch, and H. Lotze-Campen (2014a). „The Global Economic Long-Term Potential of Modern Biomass in a Climate-Constrained World“. *Environmental Research Letters*, **9**, no. 7, p. 074017.

Klein, D., G. Luderer, E. Kriegler, J. Strefler, N. Bauer, et al. (2013). „The Value of Bioenergy in Low Stabilization Scenarios: An Assessment Using REMIND-MAgPIE“. *Climatic Change*, **123**, no. 3-4, pp. 705–718.

– (2014b). „The Value of Bioenergy in Low Stabilization Scenarios: An Assessment Using REMIND-MAgPIE“. *Climatic Change*, **123**, no. 3-4, pp. 705–718.

Koen, B. V. (1985). *Definition of the Engineering Method.* ASEE Publications, Suite 200, 11 Dupont Circle, Washington, DC 20036 ($7.00).

Kovač, D. J., J. B. Simeunović, O. B. Babić, A. Č. Mišan, and I. L. Milovanović (2013). „Algae in Food and Feed | FINS“. **40**, no. 1.

Kraxner, F., E.-M. Nordström, P. Havl´k, M. Gusti, A. Mosnier, et al. (2013). „Global Bioenergy Scenarios – Future Forest Development, Land-Use Implications, and Trade-Offs“. *Biomass and Bioenergy*, **57**, pp. 86–96.

Kriegler, E., M. Tavoni, T. Aboumahboub, G. Luderer, K. Calvin, et al. (2013). „What Does the 2°c Target Imply for a Global Climate Agreement in 2020? The Limits Study on Durban Platform Scenarios“. *Climate Change Economics*, **04**, no. 04, p. 1340008.

Kucharik, C. J., A. VanLoocke, J. D. Lenters, and M. M. Motew (2013). „Miscanthus Establishment and Overwintering in the Midwest USA: A Regional Modeling Study of Crop Residue Management on Critical Minimum Soil Temperatures“. *PLOS ONE*, **8**, no. 7, e68847.

Labrecque, M. and T. I. Teodorescu (2005). „Field Performance and Biomass Production of 12 Willow and Poplar Clones in Short-Rotation Coppice in Southern Quebec (Canada)“. *Biomass and Bioenergy*, **29**, no. 1, pp. 1–9.

Laclau, J.-P., J.-P. Bouillet, and J. Ranger (2000). „Dynamics of Biomass and Nutrient Accumulation in a Clonal Plantation of Eucalyptus in Congo“. *Forest Ecology and Management*, **128**, no. 3, pp. 181–196.

Lal, R. (2008). „Sequestration of Atmospheric CO2 in Global Carbon Pools“. *Energy & Environmental Science*, **1**, no. 1, pp. 86–100.

Lambin, E. F., H. K. Gibbs, L. Ferreira, R. Grau, P. Mayaux, P. Meyfroidt, D. C. Morton, T. K. Rudel, I. Gasparri, and J. Munger (2013). „Estimating the World's Potentially Available Cropland Using a Bottom-up Approach“. *Global Environmental Change*, **23**, no. 5, pp. 892–901.

Langholtz, M., D. Carter, and D. L. Rockwood (2007). *Assessing the Economic Feasibility of Short-Rotation Woody Crops in Florida.* University of Florida Florida, UFAS Extension.

Laurance, W. F., G. R. Clements, S. Sloan, C. S. O'Connell, N. D. Mueller, et al. (2014). „A Global Strategy for Road Building". *Nature*, **513**, no. 7517, pp. 229–232.

Laureysens, I., J. Bogaert, R. Blust, and R. Ceulemans (2004). „Biomass Production of 17 Poplar Clones in a Short-Rotation Coppice Culture on a Waste Disposal Site and Its Relation to Soil Characteristics". *Forest Ecology and Management*, **187**, no. 2–3, pp. 295–309.

Lehmann, J., D. Coumou, and K. Frieler (2015). „Increased Record-Breaking Precipitation Events under Global Warming". *Climatic Change*, **132**, no. 4, pp. 501–515.

Leipprand, A. and D. Gerten (2006). „Global Effects of Doubled Atmospheric CO2 Content on Evapotranspiration, Soil Moisture and Runoff under Potential Natural Vegetation". *Hydrological Sciences Journal*, **51**, no. 1, pp. 171–185.

Lemus, R., E. C. Brummer, K. J. Moore, N. E. Molstad, C. L. Burras, and M. F. Barker (2002). „Biomass Yield and Quality of 20 Switchgrass Populations in Southern Iowa, USA". *Biomass and Bioenergy*, **23**, no. 6, pp. 433–442.

Lemus, R. and R. Lal (2005). „Bioenergy Crops and Carbon Sequestration". *Critical Reviews in Plant Sciences*, **24**, no. 1, pp. 1–21.

Lemus, R. W. (2004). „Switchgrass as an Energy Crop: Fertilization, Cultivar, and Cutting Management". PhD thesis.

Lenton, T. M. and N. E. Vaughan (2009). „The Radiative Forcing Potential of Different Climate Geoengineering Options". *Atmos. Chem. Phys.* **9**, no. 15, pp. 5539–5561.

Lenton, T. and A. Watson (2011). *Revolutions That Made the Earth.* OUP Oxford.

Lenton, T. M. (2010). „The Potential for Land-Based Biological CO2 Removal to Lower Future Atmospheric CO2 Concentration". *Carbon Management*, **1**, no. 1, pp. 145–160.

Lenton, T. M. (2011). „Early Warning of Climate Tipping Points". *Nature Climate Change*, **1**, no. 4, pp. 201–209.

Levermann, A., P. U. Clark, B. Marzeion, G. A. Milne, D. Pollard, V. Radic, and A. Robinson (2013). „The Multimillennial Sea-Level Commitment of Global Warming". *Proceedings of the National Academy of Sciences*, **110**, no. 34, pp. 13745–13750.

Licker, R., M. Johnston, J. A. Foley, C. Barford, C. J. Kucharik, C. Monfreda, and N. Ramankutty (2010). „Mind the Gap: How Do Climate and Agricultural Management Explain the ‘Yield Gap’ of Croplands around the World?“ *Global Ecology and Biogeography*, **19**, no. 6, pp. 769–782.

Lindegaard, K. N., R. I. Parfitt, G. Donaldson, T. Hunter, W. M. Dawson, E. G. A. Forbes, M. M. Carter, C. C. Whinney, J. E. Whinney, and S. Larsson (2001). „Comparative Trials of Elite Swedish and UK Biomass Willow Varieties.“ Association of Applied Biologists, pp. 183–192.

Linderson, M.-L., Z. Iritz, and A. Lindroth (2007). „The Effect of Water Availability on Stand-Level Productivity, Transpiration, Water Use Efficiency and Radiation Use Efficiency of Field-Grown Willow Clones“. *Biomass and Bioenergy*, **31**, no. 7, pp. 460–468.

Lomax, G., T. M. Lenton, A. Adeosun, and M. Workman (2015). „Investing in Negative Emissions“. *Nature Climate Change*, **5**, no. 6, pp. 498–500.

Lotze-Campen, H., A. Popp, T. Beringer, C. Müller, A. Bondeau, S. Rost, and W. Lucht (2010). „Scenarios of Global Bioenergy Production: The Trade-Offs between Agricultural Expansion, Intensification and Trade“. *Ecological Modelling*. Model-based Systems to Support Impact Assessment - Methods, Tools and Applications **221**, no. 18, pp. 2188–2196.

Lotze-Campen, H., M. von Lampe, P. Kyle, S. Fujimori, P. Havlik, et al. (2014). „Impacts of Increased Bioenergy Demand on Global Food Markets: An AgMIP Economic Model Intercomparison“. *Agricultural Economics*, **45**, no. 1, pp. 103–116.

Lovelock, J. E., R. J. Maggs, and R. J. Wade (1973). „Halogenated Hydrocarbons in and over the Atlantic“. *Nature*, **241**, no. 5386, pp. 194–196.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler (2013). „Implications of Weak Near-Term Climate Policies on Long-Term Mitigation Pathways“. *Climatic Change*.

Luderer, G., V. Bosetti, M. Jakob, M. Leimbach, J. C. Steckel, H. Waisman, and O. Edenhofer (2011). „The Economics of Decarbonizing the Energy System—results and Insights from the RECIPE Model Intercomparison“. *Climatic Change*, **114**, no. 1, pp. 9–37.

Luo, Y., D. Gerten, G. Le Maire, W. J. Parton, E. Weng, et al. (2008). „Modeled Interactive Effects of Precipitation, Temperature, and [CO2] on Ecosystem Carbon and Water Dynamics in Different Climatic Zones“. *Global Change Biology*, **14**, no. 9, pp. 1986–1999.

McElroy, G. H. and W. M. Dawson (1986). „Biomass from Short-Rotation Coppice Willow on Marginal Land“. *Biomass*, **10**, no. 3, pp. 225–240.

Meinshausen, M., S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, et al. (2011). „The RCP Greenhouse Gas Concentrations and Their Extensions from 1765 to 2300“. *Climatic Change*, **109**, no. 1-2, pp. 213–241.

Merlin, O., J. Chrirouze, A. Olioso, L. Jarlan, G. Chehbouni, and G. Boulet (2013). „An Image-Based Four-Source Surface Energy Balance Model to Estimate Crop Evapotranspiration from Solar Reflectance/Thermal Emission Data (SEB-4S)“.

Midilli, A., I. Dincer, and M. Ay (2006). „Green Energy Strategies for Sustainable Development“. *Energy Policy*, **34**, no. 18, pp. 3623–3633.

Miller, J. N., A. VanLoocke, N. Gomez-Casanovas, and C. J. Bernacchi (2015). „Candidate Perennial Bioenergy Grasses Have a Higher Albedo than Annual Row Crops“. *GCB Bioenergy*.

Monfreda, C., N. Ramankutty, and J. A. Foley (2008). „Farming the Planet: 2. Geographic Distribution of Crop Areas, Yields, Physiological Types, and Net Primary Production in the Year 2000“. *Global Biogeochemical Cycles*, **22**, no. 1, n/a–n/a.

Müller, C., B. Eickhout, S. Zaehle, A. Bondeau, W. Cramer, and W. Lucht (2007). „Effects of Changes in CO2, Climate, and Land Use on the Carbon Balance of the Land Biosphere during the 21st Century“. *Journal of Geophysical Research: Biogeosciences*, **112**, no. G2, G02032.

Nishina, K., A. Ito, D. J. Beerling, P. Cadule, P. Ciais, et al. (2014). „Quantifying Uncertainties in Soil Carbon Responses to Changes in Global Mean Temperature and Precipitation“. *Earth System Dynamics*, **5**, no. 1, pp. 197–209.

Oldemann, L., R. T. A. Hakkeling, W. G. Sombroek, and N. H. Batjes (1991). *Global Assessment of Human-Induced Soil Degradation (GLASOD)*. Tech. rep. Wageningen University & Research.

Ostberg, S., W. Lucht, S. Schaphoff, and D. Gerten (2013). „Critical Impacts of Global Warming on Land Ecosystems“. *Earth System Dynamics*, **4**, no. 2, pp. 347–357.

Ostberg, S., S. Schaphoff, W. Lucht, and D. Gerten (2015). „Three Centuries of Dual Pressure from Land Use and Climate Change on the Biosphere“. *Environmental Research Letters*, **10**, no. 4, p. 044011.

Palmer, T. (2014). „Record-Breaking Winters and Global Climate Change“. *Science*, **344**, no. 6186, pp. 803–804.

Pennington, D. (2012). *Fertilizer Requirements of the Bioenergy Crop Miscanthus*. `http://msue.anr.msu.edu/news/fertilizer_requirements_of_the_bioenergy_crop_miscanthus`.

Peters, G. P., R. M. Andrew, T. Boden, J. G. Canadell, P. Ciais, C. Le Quéré, G. Marland, M. R. Raupach, and C. Wilson (2013). „The Challenge to Keep Global Warming below 2 °C“. *Nature Climate Change*, **3**, no. 1, pp. 4–6.

Pidgeon (2013). *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society.*

Pimm, S. L., C. N. Jenkins, R. Abell, T. M. Brooks, J. L. Gittleman, L. N. Joppa, P. H. Raven, C. M. Roberts, and J. O. Sexton (2014). „The Biodiversity of Species and Their Rates of Extinction, Distribution, and Protection“. *Science*, **344**, no. 6187, p. 1246752.

Piontek, F., C. Müller, T. A. M. Pugh, D. B. Clark, D. Deryng, et al. (2014). „Multisectoral Climate Impact Hotspots in a Warming World“. *Proceedings of the National Academy of Sciences*, **111**, no. 9, pp. 3233–3238.

Pongratz, J., C. H. Reick, T. Raddatz, K. Caldeira, and M. Claussen (2011). „Past Land Use Decisions Have Increased Mitigation Potential of Reforestation“. *Geophysical Research Letters*, **38**, no. 15, p. L15701.

Pongratz, J. (2013). „Climate Science: Plant a Tree, but Tend It Well“. *Nature*, **498**, no. 7452, pp. 47–48.

Popp, A., F. Humpenöder, I. Weindl, B. L. Bodirsky, M. Bonsch, et al. (2014a). „Land-Use Protection for Climate Change Mitigation“. *Nature Climate Change*, **4**, no. 12, pp. 1095–1098.

Popp, A., S. K. Rose, K. Calvin, D. P. V. Vuuren, J. P. Dietrich, et al. (2014b). „Land-Use Transition for Bioenergy and Climate Stabilization: Model Comparison of Drivers, Impacts and Interactions with Other Land Use Based Mitigation Options“. *Climatic Change*, **123**, no. 3-4, pp. 495–509.

Portmann, F. T., S. Siebert, and P. Döll (2010). „MIRCA2000—Global Monthly Irrigated and Rainfed Crop Areas around the Year 2000: A New High-Resolution Data Set for Agricultural and Hydrological Modeling“. *Global Biogeochemical Cycles*, **24**, no. 1, GB1011.

Poulter, B., P. Cadule, A. Cheiney, P. Ciais, E. Hodson, et al. (2015). „Sensitivity of Global Terrestrial Carbon Cycle Dynamics to Variability in Satellite-Observed Burned Area“. *Global Biogeochemical Cycles*, **29**, no. 2, 2013GB004655.

Powell, T. L., D. R. Galbraith, B. O. Christoffersen, A. Harper, H. M. A. Imbuzeiro, et al. (2013). „Confronting Model Predictions of Carbon Fluxes with Measurements of Amazon Forests Subjected to Experimental Drought“. *New Phytologist*, **200**, no. 2, pp. 350–365.

Powell, T. W. R. and T. M. Lenton (2012). „Future Carbon Dioxide Removal via Biomass Energy Constrained by Agricultural Efficiency and Dietary Trends“. *Energy & Environmental Science*, **5**, no. 8, p. 8116.

Prentice, I. C., G. D. Farquhar, M. J. R. Fasham, M. L. Goulden, M. Heimann, V. J. Jaramillo, H. S. Kheshgi, C. LeQuéré, R. J. Scholes, and D. W. R. Wallace (2001). „The Carbon Cycle and Atmospheric Carbon Dioxide“. *Climate Change 2001: The Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Ed. by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. Cambridge, UK: Cambridge University Press, pp. 185–237.

Pugesgaard, S., K. Schelde, S. U. Larsen, P. E. Lærke, and U. Jørgensen (2014). „Comparing Annual and Perennial Crops for Bioenergy Production – Influence on Nitrate Leaching and Energy Balance“. *GCB Bioenergy*, n/a–n/a.

Qin, Z., Q. Zhuang, and X. Cai (2014). „Bioenergy Crop Productivity and Potential Climate Change Mitigation from Marginal Lands in the United States: An Ecosystem Modeling Perspective“. *GCB Bioenergy*, n/a–n/a.

Qin, Z., Q. Zhuang, X. Zhu, X. Cai, and X. Zhang (2011). „Carbon Consequences and Agricultural Implications of Growing Biofuel Crops on Marginal Agricultural Lands in China“. *Environmental Science & Technology*, **45**, no. 24, pp. 10765–10772.

Quéré, C. L., R. Moriarty, R. M. Andrew, J. G. Canadell, S. Sitch, et al. (2015). „Global Carbon Budget 2015“. *Earth System Science Data*, **7**, no. 2, pp. 349–396.

Rae, A. M., K. M. Robinson, N. R. Street, and G. Taylor (2004). „Morphological and Physiological Traits Influencing Biomass Productivity in Short-Rotation Coppice Poplar“. *Canadian Journal of Forest Research*, **34**, no. 7, pp. 1488–1498.

Ramankutty, N., A. T. Evan, C. Monfreda, and J. A. Foley (2008). „Farming the Planet: 1. Geographic Distribution of Global Agricultural Lands in the Year 2000“. *Global Biogeochemical Cycles*, **22**, no. 1, n/a–n/a.

Reilly, J., J. Melillo, Y. Cai, D. Kicklighter, A. Gurgel, S. Paltsev, T. Cronin, A. Sokolov, and A. Schlosser (2012). „Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-Offs“. *Environmental Science & Technology*, **46**, no. 11, pp. 5672–5679.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj (2011). „RCP 8.5-A Scenario of Comparatively High Greenhouse Gas Emissions“. *Climatic Change*, pp. 1–25.

Rogelj, J., G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi (2015a). „Energy System Transformations for Limiting End-of-Century Warming to below 1.5 [Deg]C“. *Nature Climate Change*, **5**, no. 6, pp. 519–527.

Rogelj, J., A. Reisinger, D. L. McCollum, R. Knutti, K. Riahi, and M. Meinshausen (2015b). „Mitigation Choices Impact Carbon Budget Size Compatible with Low Temperature Goals“. *Environmental Research Letters*, **10**, no. 7, p. 075003.

Rogelj, J., M. Schaeffer, M. Meinshausen, R. Knutti, J. Alcamo, K. Riahi, and W. Hare (2015c). „Zero Emission Targets as Long-Term Global Goals for Climate Protection“. *Environmental Research Letters*, **10**, no. 10, p. 105007.

– (2015d). „Zero Emission Targets as Long-Term Global Goals for Climate Protection“. *Environmental Research Letters*, **10**, no. 10, p. 105007.

Rogner, H. H., D. Zhou, R. Bradley, P. Crabbé, O. Edenhofer, B. Hare, L. Kuijpers, and M. Yamaguchi (2007). *Introduction. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

Röhl, U., T. Westerhold, T. J. Bralower, and J. C. Zachos (2007). „On the Duration of the Paleocene-Eocene Thermal Maximum (PETM)“. *Geochemistry, Geophysics, Geosystems*, **8**, no. 12, Q12002.

Rost, S., D. Gerten, A. Bondeau, W. Lucht, J. Rohwer, and S. Schaphoff (2008). „Agricultural Green and Blue Water Consumption and Its Influence on the Global Water System“. *Water Resources Research*, **44**, no. 9, W09405.

Sakschewski, B., W. von Bloh, V. Huber, C. Müller, and A. Bondeau (2014). „Feeding 10 Billion People under Climate Change: How Large Is the Production Gap of Current Agricultural Systems?“ *Ecological Modelling*, **288**, pp. 103–111.

Sanderson, M. A., R. L. Reed, W. R. Ocumpaugh, M. A. Hussey, G. Van Esbroeck, J. C. Read, C. R. Tischler, and F. M. Hons (1999). „Switchgrass Cultivars and Germplasm for Biomass Feedstock Production in Texas“. *Bioresource Technology*, **67**, no. 3, pp. 209–219.

Sanderson, M. A. (2008). „Upland Switchgrass Yield, Nutritive Value, and Soil Carbon Changes Under Grazing and Clipping“. *Agronomy Journal*, **100**, no. 3, p. 510.

Sanford, T., P. C. Frumhoff, A. Luers, and J. Gulledge (2014). „The Climate Policy Narrative for a Dangerously Warming World“. *Nature Climate Change*, **4**, no. 3, pp. 164–166.

Schaeffer, M., B. Eickhout, M. Hoogwijk, B. Strengers, D. van Vuuren, R. Leemans, and T. Opsteegh (2006). „CO2 and Albedo Climate Impacts of Extratropical Carbon and Biomass Plantations“. *Global Biogeochemical Cycles*, **20**, no. 2, GB2020.

Schamm, K., M. Ziese, A. Becker, P. Finger, A. Meyer-Christoffer, U. Schneider, M. Schröder, and P. Stender (2014). „Global Gridded Precipitation over Land: A Description of the New GPCC First Guess Daily Product". *Earth System Science Data*, **6**, no. 1, pp. 49–60.

Schaphoff, S., U. Heyder, S. Ostberg, D. Gerten, J. Heinke, and W. Lucht (2013). „Contribution of Permafrost Soils to the Global Carbon Budget". *Environmental Research Letters*, **8**, no. 1, p. 014026.

Schellnhuber, H. J., S. Rahmstorf, and R. Winkelmann (2016). „Why the Right Climate Target Was Agreed in Paris". *Nature Climate Change*, **6**, no. 7, pp. 649–653.

Schmer, M. R., K. P. Vogel, R. B. Mitchell, and R. K. Perrin (2008). „Net Energy of Cellulosic Ethanol from Switchgrass". *Proceedings of the National Academy of Sciences*, **105**, no. 2, pp. 464–469.

Scholz, V. and R. Ellerbrock (2002). „The Growth Productivity, and Environmental Impact of the Cultivation of Energy Crops on Sandy Soil in Germany". *Biomass and Bioenergy*, **23**, no. 2, pp. 81–92.

Schwarz, H. (1993). „Miscanthus Sinensis 'Giganteus' Production on Several Sites in Austria". *Biomass and Bioenergy*, **5**, no. 6, pp. 413–419.

Searchinger, T. D., L. Estes, P. K. Thornton, T. Beringer, A. Notenbaert, D. Rubenstein, R. Heimlich, R. Licker, and M. Herrero (2015). „High Carbon and Biodiversity Costs from Converting Africa/'s Wet Savannahs to Cropland". *Nature Climate Change*, **advance online publication**.

Sharma, N., I. Piscioneri, and V. Pignatelli (2003). „An Evaluation of Biomass Yield Stability of Switchgrass (Panicum Virgatum L.) Cultivars". *Energy Conversion and Management*, **44**, no. 18, pp. 2953–2958.

Shepherd, J. G. (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. http://eprints.soton.ac.uk/156647/. Monograph.

Sillmann, J., T. M. Lenton, A. Levermann, K. Ott, M. Hulme, F. Benduhn, and J. B. Horton (2015). „Climate Emergencies Do Not Justify Engineering the Climate". *Nature Climate Change*, **5**, no. 4, pp. 290–292.

Singarayer, J. S., A. Ridgwell, and P. Irvine (2009). „Assessing the Benefits of Crop Albedo Bio-Geoengineering". *Environmental Research Letters*, **4**, no. 4, p. 045110.

Sitch, S., B. Smith, I. C. Prentice, A. Arneth, A. Bondeau, et al. (2003). „Evaluation of Ecosystem Dynamics, Plant Geography and Terrestrial Carbon Cycling in the LPJ Dynamic Global Vegetation Model". *Global Change Biology*, **9**, no. 2, pp. 161–185.

Sladden, S. E., D. I. Bransby, and G. E. Aiken (1991). „Biomass Yield, Composition and Production Costs for Eight Switchgrass Varieties in Alabama". *Biomass and Bioenergy*, **1**, no. 2, pp. 119–122.

Slade, R., A. Bauen, and R. Gross (2014). „Global Bioenergy Resources“. *Nature Climate Change*, **4**, no. 2, pp. 99–105.

Smeets, E. M. W., A. P. C. Faaij, I. M. Lewandowski, and W. C. Turkenburg (2007). „A Bottom-up Assessment and Review of Global Bio-Energy Potentials to 2050“. *Progress in Energy and Combustion Science*, **33**, no. 1, pp. 56–106.

Smil, V. (2003). *The Earth's Biosphere: Evolution, Dynamics, and Change*. MIT Press.

Smith, P. (2016). „Soil Carbon Sequestration and Biochar as Negative Emission Technologies“. *Global Change Biology*, n/a–n/a.

Smith, P., S. J. Davis, F. Creutzig, S. Fuss, J. Minx, et al. (2016). „Biophysical and Economic Limits to Negative CO2 Emissions“. *Nature Climate Change*, **6**, no. 1, pp. 42–50.

Smith, P., H. Haberl, A. Popp, K.-h. Erb, C. Lauk, et al. (2013a). „How Much Land-Based Greenhouse Gas Mitigation Can Be Achieved without Compromising Food Security and Environmental Goals?“ *Global Change Biology*, **19**, no. 8, pp. 2285–2302.

– (2013b). „How Much Land-Based Greenhouse Gas Mitigation Can Be Achieved without Compromising Food Security and Environmental Goals?“ *Global Change Biology*, **19**, no. 8, pp. 2285–2302.

Souza, G. M., R. L. Victoria, C. A. Joly, and L. M. Verdade (2015). *Bioenergy & Sustainability: Bridging the Gaps*. Paris Cedex: Scientific Committee on Problems of the Environment (SCOPE).

Stape, J. L., D. Binkley, M. G. Ryan, S. Fonseca, R. A. Loos, et al. (2010). „The Brazil Eucalyptus Potential Productivity Project: Influence of Water, Nutrients and Stand Uniformity on Wood Production“. *Forest Ecology and Management*, **259**, no. 9, pp. 1684–1694.

Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, et al. (2015). „Planetary Boundaries: Guiding Human Development on a Changing Planet“. *Science*, **347**, no. 6223, p. 1259855.

Stocker, T., D. Qin, G.-K. Plattner, M. Tignor, S. Allen, and J. Boschung (2013a). „IPCC, 2013: Summary for Policymakers.“ *IPCC, 2013: Summary for Policymakers. Climate Change 2013 - The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Stocker, T. F. (2013). „The Closing Door of Climate Targets“. *Science*, **339**, no. 6117, pp. 280–282.

Stocker, T., D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, B. Bex, and B. M. Midgley, eds. (2013b). *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.

Strengers, B., C. Müller, M. Schaeffer, R. Haarsma, C. Severijns, D. Gerten, S. Schaphoff, R. van den Houdt, and R. Oostenrijk (2010). „Assessing 20th Century Climate–vegetation Feedbacks of Land-Use Change and Natural Vegetation Dynamics in a Fully Coupled Vegetation–climate Model“. *International Journal of Climatology*, **30**, no. 13, pp. 2055–2065.

Stričević, R., Z. Dželetović, N. Djurović, and M. Cosić (2014). „Application of the AquaCrop Model to Simulate the Biomass of Miscanthus x Giganteus under Different Nutrient Supply Conditions“. *GCB Bioenergy*, n/a–n/a.

Taylor, K., R. Stouffer, and G. Meehl (2009). „A Summary of the CMIP5 Experiment Design, Htt Ps“. *cmip. llnl. gov/cmip5/docs/Taylor CMIP5 design. pdf (last access: 26 July 2010)*.

Thomson, A. M., K. V. Calvin, S. J. Smith, G. P. Kyle, A. Volke, et al. (2011). „RCP4.5: A Pathway for Stabilization of Radiative Forcing by 2100“. *Climatic Change*, **109**, no. 1-2, pp. 77–94.

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer (2001). „The Role of Fire Disturbance for Global Vegetation Dynamics: Coupling Fire into a Dynamic Global Vegetation Model“. *Global Ecology and Biogeography*, **10**, no. 6, pp. 661–677.

Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky (2002). „Agricultural Sustainability and Intensive Production Practices“. *Nature*, **418**, no. 6898, pp. 671–677.

Tilman, D., J. Hill, and C. Lehman (2006). „Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass“. *Science*, **314**, no. 5805, pp. 1598–1600.

Tokarska, K. B. and K. Zickfeld (2015). „The Effectiveness of Net Negative Carbon Dioxide Emissions in Reversing Anthropogenic Climate Change“. *Environmental Research Letters*, **10**, no. 9, p. 094013.

Tuomisto, H. L. (2010). „Food Security and Protein Supply -Cultured Meat a Solution?“ **102**.

UN (2004). „World Population Prospects: The 2004 Revision.“ *United Nations—Department for Economic and Social Information and Policy Analysis, New York*.

UNFCCC (2015). *Report of the Conference of the Parties on Its Twenty*. `http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf`.

United Nations Population Division, D. o. E. and S. Affairs (2015). *World Population Prospects: The 2015 Revision, Methodology of the United Nations Population Estimates and Projections.* Working Paper No. ESA/P/WP.242. New York, NY.

van der Werf, H. M. G., W. J. M. Meijer, E. W. J. M. Mathijssen, and A. Darwinkel (1992). „Potential Dry Matter Production of Miscanthus Sinensis in The Netherlands“. *Industrial Crops and Products.* Proceedings of the European Symposium on Industrial Crops and Products **1**, no. 2–4, pp. 203–210.

van Minnen, J. G. van, B. J. Strengers, B. Eickhout, R. J. Swart, and R. Leemans (2008). „Quantifying the Effectiveness of Climate Change Mitigation through Forest Plantations and Carbon Sequestration with an Integrated Land-Use Model“. *Carbon Balance and Management*, **3**, no. 1, p. 3.

van Vuuren, D. P. van, M. G. J. den Elzen, P. L. Lucas, B. Eickhout, B. J. Strengers, B. van Ruijven, S. Wonink, and R. van Houdt (2007). „Stabilizing Greenhouse Gas Concentrations at Low Levels: An Assessment of Reduction Strategies and Costs“. *Climatic Change*, **81**, no. 2, pp. 119–159.

van Vuuren, D. P., E. Stehfest, M. G. J. den Elzen, J. van Vliet, and M. Isaac (2010). „Exploring IMAGE Model Scenarios That Keep Greenhouse Gas Radiative Forcing below 3 W/M2 in 2100“. *Energy Economics*, **32**, no. 5, pp. 1105–1120.

van Vuuren, D. P., J. van Vliet, and E. Stehfest (2009). „Future Bio-Energy Potential under Various Natural Constraints“. *Energy Policy*, **37**, no. 11, pp. 4220–4230.

van Vuuren, D., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. Hurtt, T. Kram, V. Krey, J. Lamarque, et al. (2011a). „The Representative Concentration Pathways: An Overview“. *Climatic Change*, pp. 1–27.

van Vuuren, D., E. Stehfest, M. G. J. den Elzen, T. Kram, J. van Vliet, et al. (2011b). „RCP2.6: Exploring the Possibility to Keep Global Mean Temperature Increase below 2°C“. *Climatic Change*, **109**, no. 1-2, pp. 95–116.

Vaughan, N. E. and T. M. Lenton (2011). „A Review of Climate Geoengineering Proposals“. *Climatic Change*, **109**, no. 3-4, pp. 745–790.

Wani, S. P., G. Chander, K. L. Sahrawat, C. Srinivasa Rao, G. Raghvendra, P. Susanna, and M. Pavani (2012). „Carbon Sequestration and Land Rehabilitation through Jatropha Curcas (L.) Plantation in Degraded Lands“. *Agriculture, Ecosystems & Environment*, **161**, pp. 112–120.

Warszawski, L., K. Frieler, V. Huber, F. Piontek, O. Serdeczny, and J. Schewe (2014). „The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project Framework“. *Proceedings of the National Academy of Sciences*, **111**, no. 9, pp. 3228–3232.

Watanabe, S., S. Kanae, S. Seto, P. J.-F. Yeh, Y. Hirabayashi, and T. Oki (2012). „Intercomparison of Bias-Correction Methods for Monthly Temperature and Precipitation Simulated by Multiple Climate Models". *Journal of Geophysical Research: Atmospheres*, **117**, no. D23, p. D23114.

Weisdorf, J. L. (2005). „From Foraging To Farming: Explaining The Neolithic Revolution". *Journal of Economic Surveys*, **19**, no. 4, pp. 561–586.

Wieder, W. R., C. C. Cleveland, W. K. Smith, and K. Todd-Brown (2015). „Future Productivity and Carbon Storage Limited by Terrestrial Nutrient Availability". *Nature Geoscience*, **8**, no. 6, pp. 441–444.

Wirsenius, S. (2000). „Human Use of Land and Organic Materials: Modeling the Turnover of Biomass in the Global Food System". Doctoral thesis. Chalmers University of Technology.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S. J. Smith, A. Janetos, and J. Edmonds (2009). „Implications of Limiting CO2 Concentrations for Land Use and Energy". *Science*, **324**, no. 5931, pp. 1183–1186.

Woolf, D., J. E. Amonette, F. A. Street-Perrott, J. Lehmann, and S. Joseph (2010). „Sustainable Biochar to Mitigate Global Climate Change". *Nature Communications*, **1**, p. 56.

Xie, J., J. Guo, Z. Yang, Z. Huang, G. Chen, and Y. Yang (2013). „Rapid Accumulation of Carbon on Severely Eroded Red Soils through Afforestation in Subtropical China". *Forest Ecology and Management*. Shaping Forest Management to Climate Change **300**, pp. 53–59.

Yu, L., G. Ding, Z. Huai, and H. Zhao (2013). „Natural Variation of Biomass Yield and Nutrient Dynamics in Miscanthus". *Field Crops Research*, **151**, pp. 1–8.

Zeng, N. (2008). „Carbon Sequestration via Wood Burial". *Carbon Balance and Management*, **3**, no. 1, p. 1.

Zickfeld, K., M. Eby, A. J. Weaver, K. Alexander, E. Crespin, et al. (2013). „Long-Term Climate Change Commitment and Reversibility: An EMIC Intercomparison". *Journal of Climate*, **26**, no. 16, pp. 5782–5809.

Zickfeld, K. and T. Herrington (2015). „The Time Lag between a Carbon Dioxide Emission and Maximum Warming Increases with the Size of the Emission". *Environmental Research Letters*, **10**, no. 3, p. 031001.

Zickfeld, K., A. H. MacDougall, and H. D. Matthews (2016). „On the Proportionality between Global Temperature Change and Cumulative CO 2 Emissions during Periods of Net Negative CO 2 Emissions". *Environmental Research Letters*, **11**, no. 5, p. 055006.